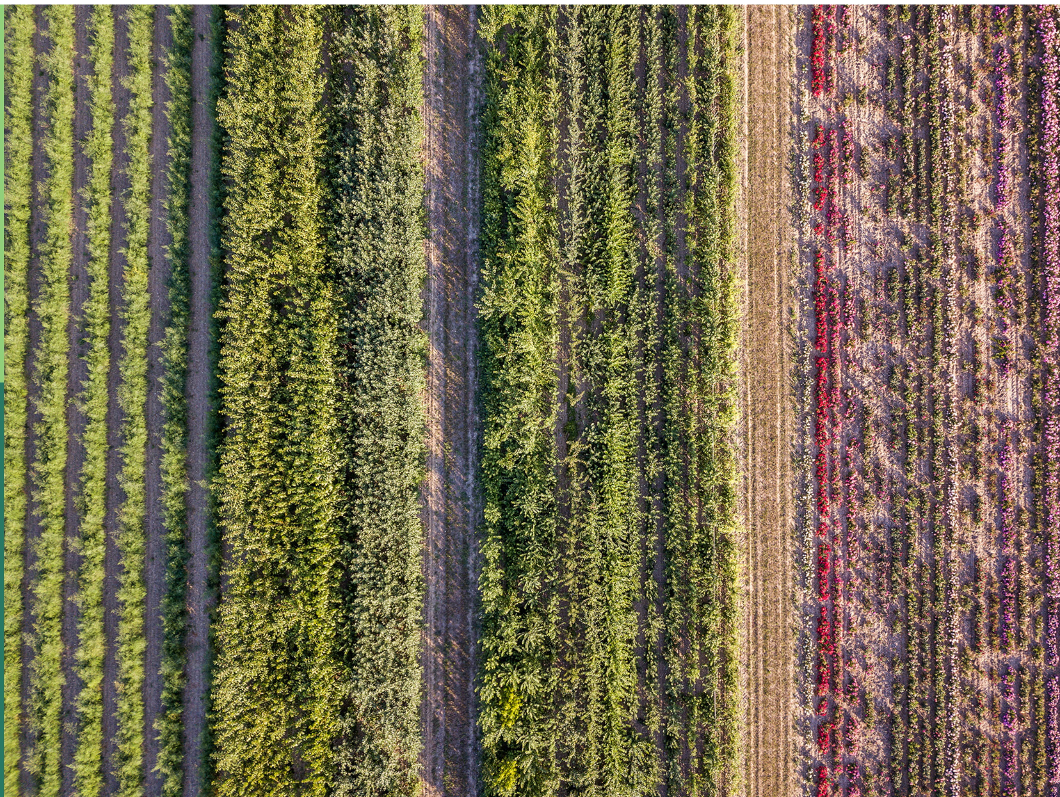
frontiers | Research Topics

Circular economy and sustainability in the agro-food system

Edited by
Marzia Ingrassia, Maurizio Cellura, Claudio Bellia,
Luca Altamore and Sonia Longo

Published in
Frontiers in Sustainable Food Systems



ISSN 1664-8714
ISBN 978-2-8325-4342-9
DOI 10.3389/978-2-8325-4342-9

About Frontiers

Frontiers is more than just an open access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers journal series

The Frontiers journal series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the *Frontiers journal series* operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews. Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the *Frontiers journals series*: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area.

Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers editorial office: frontiersin.org/about/contact

Circular economy and sustainability in the agro-food system

Topic editors
Marzia Ingrassia — Università degli Studi di Palermo, Italy
Maurizio Cellura — University of Palermo, Italy
Claudio Bellia — University of Catania, Italy
Luca Altamore — University of Palermo, Italy
Sonia Longo — University of Palermo, Italy

Citation
Ingrassia, M., Cellura, M., Bellia, C., Altamore, L., Longo, S., eds. (2024). *Circular economy and sustainability in the agro-food system*. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-4342-9

Table of contents

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 24 November 2022
DOI 10.3389/fsufs.2022.1010890

Check for updates

OPEN ACCESS

EDITED BY
Claudio Bellia,
University of Catania, Italy

REVIEWED BY
Zina Flagella,
Università degli Studi di Foggia, Italy
Miloš Radosavljević,
University of Novi Sad, Serbia

*CORRESPONDENCE
Michela Verni
michela.verni@uniba.it

†These authors have contributed equally to this work and share first authorship

SPECIALTY SECTION
This article was submitted to Waste Management in Agroecosystems, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 03 August 2022
ACCEPTED 04 November 2022
PUBLISHED 24 November 2022

CITATION
Cacace C, Cocozza C, Traversa A, Coda R, Rizzello CG, Pontonio E, De Mastro F, Brunetti G and Verni M (2022) Potential of native and bioprocessed brewers' spent grains as organic soil amendments. *Front. Sustain. Food Syst.* 6:1010890. doi: 10.3389/fsufs.2022.1010890

Potential of native and bioprocessed brewers' spent grains as organic soil amendments

Claudio Cacace[1†], Claudio Cocozza[1†], Andreina Traversa[1], Rossana Coda[2,3], Carlo Giuseppe Rizzello[4], Erica Pontonio[1], Francesco De Mastro[1], Gennaro Brunetti[1] and Michela Verni[1*]

[1]Department of Soil, Plant, and Food Sciences, University of Bari "Aldo Moro", Bari, Italy, [2]Department of Food and Nutrition Sciences, University of Helsinki, Helsinki, Finland, [3]Faculty of Agriculture and Forestry, Helsinki Institute of Sustainability Science, University of Helsinki, Helsinki, Finland, [4]Department of Environmental Biology, "Sapienza" University of Rome, Rome, Italy

Introduction: The use of novel soil amendments and the exploitation of plant growth-promoting microorganisms are considered promising tools for developing a more sustainable agriculture in times when ensuring high-yield productions with limited resources is essential.

Methods: In this study, the potential of brewers' spent grain (BSG), the major by-product of the brewing industry, as organic soil amendment, was investigated. Bioprocessed BSG, obtained by an enzymatic treatment coupled with fermentation, together with native BSG, were used as amendments in a pot-trial. An integrated analytical approach aimed at assessing the modification of the physicochemical properties of a typical Mediterranean alkaline agricultural soil, and the plant growth-promoting effect on escarole (*Cichorium endivia* var. *Cuartana*), was carried out.

Results: The use of biomasses led to soil organic content and total nitrogen content up to 72 and 42% higher, compared to the unamended soils. Moreover, the lower pH and the higher organic acids content doubled phosphorus availability. Although the number of leaves per plant in escaroles from pots amended with native and bioprocessed BSG did not show any difference compared to plants cultivated on unamended pots, the average fresh weight per escarole head, was higher in pots amended with bioprocessed BSG.

Discussion: Hence, the results collected so far encourage BSG application for agricultural purpose, while solving the problem of disposing of such abundant side stream.

KEYWORDS

organic waste, sustainable agriculture, brewers' spent grain, lactic acid bacteria, soil amendment

Introduction

Beer is one of the most consumed beverages across the world and its major byproduct is represented by brewers' spent grain (BSG). BSG is generated during the malting mashing processes of brewing and comprises the outer layers of barley grains and, of the other cereals potentially used. Every 100 L of beer produced, 20 kg of BSG is generated (Yoo et al., 2021), leading to production volumes of 39 million tons of BSG every year worldwide, 3.4 million of which, just in Europe (Bianco et al., 2020). A small quantity of BSG is used as low-value animal feed, while the remaining part is discarded (Ravindran and Jaiswal, 2016). Such residual biomass represents, on one hand, a huge cost and risk for the environment, on the other, a source of organic carbon and nutrients that could be valorised as soil amendment.

BSG contains up to 20% of proteins, composed mainly by essential amino acids, it is also rich in cellulose (17%) and arabinoxylans and shows an acidic pH due to the presence of organic acids (Mussatto et al., 2006). Although the amount of available fermentable sugar is low, BSG can be used as substrate for fermentation with lactic acid bacteria (LAB) whose activity further lowers the pH and enhances the release of phenolic compounds, flavonoids, and protein derivatives (Verni et al., 2019, 2020). It was also showed that fermentation of BSG by *Lactiplantibacillus plantarum* or *Leuconostoc pseudomesenteroides* induces an overexpression of genes involved in the metabolism of arabinose and xylose, the most abundant sugars composing BSG arabinoxylans (Acin-Albiac et al., 2022).

Nowadays ensuring high production yields with limited resources is of utmost importance to guarantee the sustainability of the global food system. Amendments with residual biomasses are highly recommended because they restore fertility of degraded soils (Abdelrahman et al., 2020), improve the quality of growing substrates in pot cultivation (Mininni et al., 2015), positively influence both chemical and microbiological soil properties (Ozores-Hampton et al., 2011), and allow carbon sequestration (Zhang et al., 2012). For example, for alkaline soils, which are characterized by high pH values leading to the precipitation of iron as iron oxyhydroxides and to the adsorption of phosphate by soil minerals (Sposito, 2016), application of organic matter is essential to increase yields; and BSG, native and bioprocessed, used as soil amendments, besides providing organic matter could provide several benefits. Organic acids could be involved in the competition for phosphate sorption sites, helping the desorption of P and increasing its availability (Brunetti et al., 2019), as well as in the solubilization of iron by lowering the pH (Cocozza and Ercolani, 1997). In addition, LAB are plant growth promoting microorganisms (PGPM) that can act as biocontrol agents, help plants to withstand biotic and abiotic stress and produce compounds that directly stimulate plant growth (Lamont et al., 2017). From an environmental perspective, bacterial species belonging to the former genus *Lactobacillus* are among the microorganisms able to bioaccumulate metals. Ameen et al. (2020) showed that the former *Lactobacillus plantarum* (recently reclassified as *Lactiplantibacillus plantarum*) absorbed on the surface and inside the cells a great amount of Ni^{2+} and Cr^{2+} from industrial wastewaters. The superficial adsorption is possibly due to the electrostatic interaction of metals with the functional groups of the bacterial cell wall (Kargar and Shirazi, 2020).

Based on the above consideration, we hypothesized that the integration of BSG into Mediterranean alkaline agricultural soils could positively affect their physicochemical properties and promote plant growth. In this framework, this study aimed at investigating the potential of BSG as organic soil amendment, referring to a proof-of-concept escarole cultivation model (Figure 1). In particular, brewers' spent grain, native or processed (bBSG) according to a biotechnological protocol previously optimized for the release of phenolic compounds and bioactive peptides through enzymatic treatment and LAB fermentation (Verni et al., 2020), were used in a pot trial. An integrated approach for the characterization of native and processed BSG amended soils and plants was applied.

Materials and methods

BSG-based amendments preparation and characterization

Raw material, enzymes, and microorganisms

BSG was kindly provided by Peroni brewery (Bari, Italy) and had the following proximal composition: moisture 80%; protein 21% of dry matter (d.m.); fat 10.9% of d.m.; cellulose 22.5% of d.m.; hemicellulose, 25% of d.m, lignin, 15.3% of d.m; ashes, 5.1% of d.m.

Lactiplantibacillus plantarum PU1, belonging to the Culture Collection of the Department of Soil, Plant and Food Sciences (University of Bari, Italy), selected as starter based on the kinetics of growth and acidification and the ability to increase antioxidant activity of BSG (Verni et al., 2020), was used in this study. The strain was routinely propagated on De Man, Rogosa and Sharpe (MRS) medium (Oxoid, Basingstoke, Hampshire, UK) at 30°C. Before inoculation it was cultivated until the late exponential phase of growth (ca. 10 h), harvested by centrifugation at 10,000 x g for 10 min at 4°C, washed twice in 50 mM sterile phosphate buffer (4°C, pH 7.0), resuspended in sterile distilled water, and used to inoculate BSG.

The commercial hydrolytic enzyme, Depol™ 761P (Biocatalysts, Chicago, IL), a preparation derived from *Bacillus subtilis* having xylanase activity (14,670 nkat g^{-1}), was used for the BSG treatment before fermentation.

Bioprocessing

BSG bioprocessing was carried out as described by Verni et al. (2020). Briefly, BSG homogenized with water at a 60:40 ratio was added of Depol™ 761P (100 nkat g^{-1}) and incubated at 50°C for 5 h. After the enzymatic treatment, *L. plantarum* PU1, cultivated as above described, was inoculated (initial cell density ca. 7.5 log cfu g^{-1}) and the mixture incubated at 30°C for 24 h.

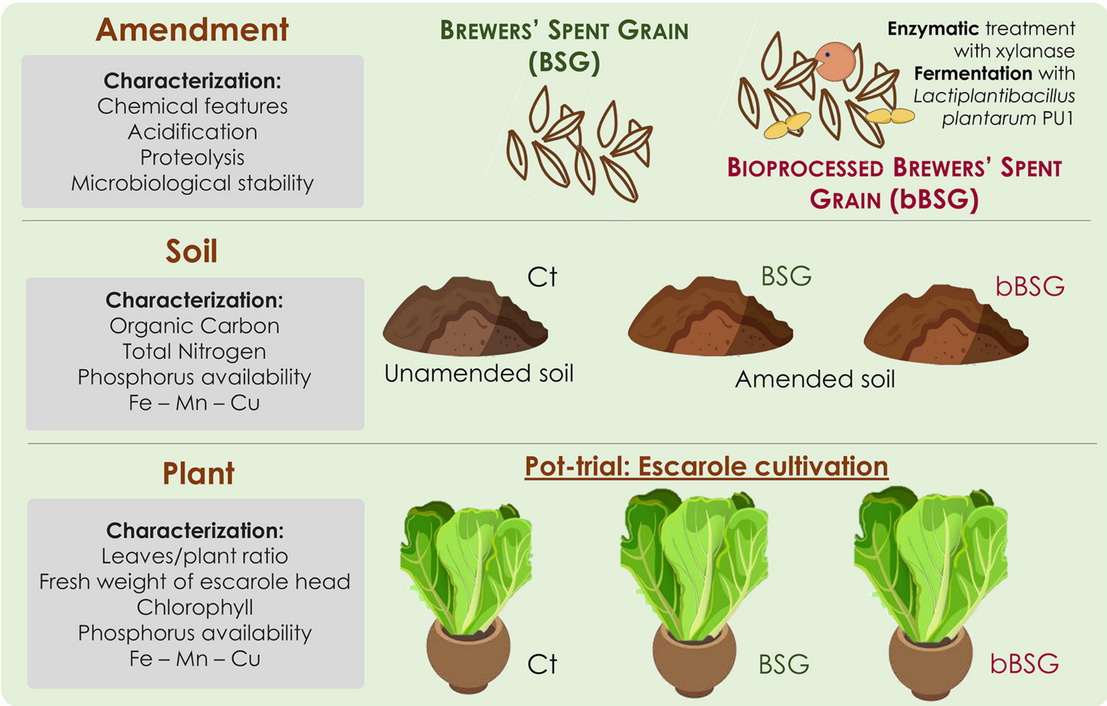


FIGURE 1
Experimental design.

Characterization of brewers' spent grain biomasses

Fermentation was monitored by measuring, before and after incubation, pH and enumerating presumptive LAB using MRS (Oxoid, Basingstoke, Hampshire, United Kingdom) agar medium, supplemented with cycloheximide (0.1 g L^{-1}). Plates were incubated in anaerobiosis condition (AnaeroGen and AnaeroJar, Oxoid) at 30°C for 48 h. The amendments were also characterized for the presence of yeasts, molds, and *Enterobacteriaceae*. Yeasts and molds were cultivated on Yeast Peptone Dextrose Agar medium (Sigma-Merck, Darmstadt, Germany), supplemented with chloramphenicol (0.1 g L^{-1}), through pour and spread plate enumeration, respectively, and incubated at 25°C whereas *Enterobacteriaceae* were determined on Violet Red Bile Glucose Agar (Oxoid) at 37°C for 24 h. pH values were determined by a pH meter (Model 507, Crison, Milan, Italy) with a food penetration probe. The AACC method 02–31.01 (AACC, 2010) was used for the determination of total titratable acidity (TTA) of samples and expressed as the amount (mL) of 0.1M NaOH necessary to reach pH of 8.4. Native and bioprocessed spent grain were also characterized for electrical conductivity (EC), moisture, total nitrogen (TN), total phosphorous (TP) and organic carbon (OC) contents, following the methods by Trinchera et al. (2006). The moisture, expressed as percentage of the initial weight, was determined by drying samples at 105°C overnight. The EC was measured on sample/water extracts (1:10 w/v) after shaking for 30 min using a Hanna Edge® EC instrument. The TN content was determined by the Kjeldahl method, while, according to Ciavatta et al. (1989), the OC content was determined by dichromate oxidation and subsequent titration with ferrous sulfate. The total P content was measured spectrophotometrically at 650 nm, after incinerating biomass samples at 550°C, suspending ashes in 10% hydrochloric acid solution, and developing the blue color in the filtered solution in accordance with the Olsen (1954).

Water/salt-soluble extracts (WSE) of the biomasses were prepared according to the method originally described by Osborne and modified by Weiss et al. (1993) using 50 mM Tris–HCl (pH 8.8). After centrifugation, the supernatants were used to determine sugars, organic acids, peptides, and total free amino acids (TFAA) concentration.

Glucose was measured using the D-Fructose D-Glucose Assay Kit K-FRUGL (Megazyme International Ireland Limited, Bray, Ireland), following the manufacturer's instructions, whereas organic acids were quantified by High Performance Liquid Chromatography (HPLC), using an ÄKTA Purifier system (GE Healthcare, Buckinghamshire, UK) equipped with an Aminex HPX-87H column (ion exclusion, Biorad, Richmond, CA), as described by Rizzello et al. (2010).

For the analysis of peptides, WSE were treated with trifluoroacetic acid (0.05% wt/vol), centrifuged (10,000 x g for 10 min), and subject to dialysis (cut-off 500 Da) to remove proteins and free amino acids, respectively. Then, peptides concentration was determined by the *o*-phtaldialdehyde method as described by Church et al. (1983), and dialysates analyzed through Reversed-Phase Fast Performance Liquid Chromatography (RP-FPLC), using an ÄKTA FPLC equipped with a Resource RPC column, with the UV detector operating at 214 nm (GE Healthcare Bio-Sciences AB, Uppsala, Sweden) as described by Rizzello et al. (2010). TFAA were analyzed by a Biochrom 30+ series Automatic Amino Acid Analyzer (Biochrom Ltd., Cambridge Science Park, United Kingdom), equipped with a Li-cation-exchange column (4.6 x 200 mm internal diameter) (De Pasquale et al., 2021).

Pot trials

Experimental design

An alkaline and tilled soil classified Haplic and Petric Calcisol, according to IUSS Working Group WRB (2015), was collected in Southern Italy, air dried and used for the pot experiments. Treatments were: (i) not amended soil, without plant (CTA); (ii) soil amended with BSG, without plant (BSGA); (iii) soil amended with bBSG, without plant (bBSGA); (iv) not amended soil, with plant (CTP); (v) soil amended with BSG, with plant (BSGP); (vi) soil amended with bBSG and with plant (bBSGP). Pots were distributed in a completely randomized design with three replications for each treatment, for a total of 18 experimental pots, and the trial was performed in a greenhouse at the University of Bari, Italy. The amended pots received BSG or bBSG at a dose of about 25,000 kg ha^{-1} according to the good local agricultural practices (Abdeldaym et al., 2018). Thirty-days-old seedlings of *Cichorium endivia* var. *Cuartana,* a variety of escarole, were transplanted at the end of the first period of February 2020 and the trial was stopped at the beginning of April. The first irrigation was performed immediately after the transplanting for the rooting and establishment of the plants. The subsequent irrigations were carried out when water lost by evapotranspiration (ET) reached about 40% of the available water depletion in the soil. The ET was calculated utilizing values of a class A pan evaporation and following the FAO procedure (Allen et al., 1998). During the trial, the temperature ranged from 5°C in the night to 23°C at mid-day, and all pots did not receive any further kind of fertilization. The escarole was intended for the fresh consumption, as salads, or cooked, as a side dish.

Soil characterization

The soil was characterized at the beginning of the trial (T0) for pH, EC, TN, available phosphorous (P_{ava}), and OC content, according to the conventional analytical methods described by Sparks et al. (1996). Briefly, the pH was measured in deionized water (pH_{H2O}) and in 1 M KCl (pH_{KCl}) suspensions at 1:2.5 soil to liquid ratio, whereas the electrical conductivity (EC) was measured in filtrates from a 1:2 soil to water ratio. The TN content was determined by the Kjeldahl method. The OC was measured by dichromate oxidation and ferrous sulfate titration according to the Walkley-Black method (De Vos et al., 2007). The P_{ava} was extracted with a 0.5 M $NaHCO_3$ solution and determined spectrophotometrically at 650 nm, according to the Olsen (1954). Diethylenetriaminepentaacetic acid (DTPA)-extractable fractions of Mn, Fe, and Cu were obtained from a 1:2 soil to DTPA solution. DTPA extracts were filtered by gravity through Whatman No. 42 filter paper, and the solutions were then analyzed using an inductively coupled plasma iCAP 6000 Series ICP-OES Spectrometer (Thermo Electron Corporation, Walthman (MA), USA). Particle size analysis was determined by the pipette method.

At the end of the experiment, all soils were analyzed again to investigate the effects of native and bioprocessed BSG in the presence and in absence of plants on soil parameters with respect to T0.

Plant characterization

To verify the effects of BSG and bBSG on plant during the trial, indirect measurements of the chlorophyll content were carried out using SPAD-502 (Konica Minolta, Japan). At the end of the test (50 days from transplanting) the number of plant leaves was recorded, as well as their fresh and dry weight to determine production yield of each treatment. Moreover, leaf samples were analyzed for their P, Mn, Fe, and Cu content, aiming at verifying the effects of each treatment on leaf composition. The total P was obtained according to Trinchera et al. (2006). The total Mn, Fe, and Cu content were determined using the microwave-assisted acid digestion method, adding a Suprapur® HNO_3:H_2O_2:HCl mixture (6:1:1, *v:v:v*) to each sample. At the end of the digestion, samples were cooled, filtered through Whatman No. 42 filter paper, diluted with distilled Milli-Q Reagent grade water and, finally, analyzed by means of an inductively coupled plasma iCAP 6000 Series ICP-OES Spectrometer (Thermo Electron Corporation).

Statistical analysis

Experimental data were tested against the normal distribution of variables (Shapiro—Wilk test) and the homogeneity of variance (Bartlett test) using R studio. The variables normally distributed with homogeneity of variances verified were subjected to an ANOVA and HSD test.

Results

Biomasses characterization

In bBSG, the initial cell density of presumptive LAB corresponded to the targeted inoculum and, after fermentation, increased of ca. 1 log cycle, reaching 8.32 ± 0.12 log cfu g^{-1}. The presence of potentially spoiling microorganisms was also assessed. Yeasts and molds in BSG were 4.7 ± 0.3 and 1.2 ± 0.2 log cfu g^{-1}, respectively, whereas *Enterobacteriaceae* were 3.3 ± 0.1 log cfu g^{-1}. After bioprocessing, compared to BSG, a significant decrease of yeasts and molds was observed, remaining below 2.5 log cfu g^{-1}, whereas *Enterobacteriaceae* were not detected.

Fermentation led to a relevant acidification. The pH decreased from 4.49 ± 0.15 of BSG to 3.75 ± 0.11 of bBSG, with a production of roughly 68 and 13 mmol kg^{-1} d.m. of lactic and acetic acid, respectively, which were detected in traces in native BSG. As consequence, TTA value was significantly higher in bBSG (11.72 ± 0.62 mL) compared to BSG (3.59 ± 0.21 mL). Glucose was not detected in both biomasses.

Bioprocessing of the biomass led to an increase in peptides concentration of ca. 20%, reaching 75 mg g^{-1} d.m. in bBSG. This trend was confirmed by the FPLC chromatograms, where although the number of total peaks detected was lower in bBSG, compared to BSG, a higher total area was found after bioprocessing (1,472 ± 80 against 854 ± 42 mAU*mL, respectively). Moreover, the treatment led to a shift toward less hydrophilic peptides. Indeed, almost 60% of all peptides detected in bBSG eluted in the range 46–100% of acetonitrile, 20% more than BSG. On the contrary, TFAA significantly ($P < 0.05$) decreased after bioprocessing reaching 980 mg kg^{-1} d.m. against the 3.7 g kg^{-1} d.m. found in native BSG.

As shown in Table 1, bioprocessing increased the EC content of the biomass, while BSG showed significantly higher total phosphorous content compared to bBSG. The content of OC, TN, and the C/N ratio did not significantly differ between biomasses.

Soil characterization

Table 2 reports soils physicochemical properties at the beginning (T0) and at the end of the trial. The pH_{H2O} of T0, CTP and CTA was alkaline and ranged from 8.37 ± 0.12 to 8.71 ± 0.04, while that of soils with bBSG and BSG supplementation was significantly lower, even if they did not show significant differences among each other. In contrast, the pH_{KCl} of all soils did not show any significant difference. Treated soils, with or without plant, had significantly higher OC and TN than T0 and corresponding control pots. The availability of P increased significantly with the addition of the biomasses and with plants, while the P_{ava} content raised only in treated pots without plants.

No significant differences were observed in the content of available iron, manganese, and copper in soils, with or without plants, and treated with bioprocessed or native BSG (data not shown).

Plant characterization

Table 3 reports the mean biometric features of escaroles at the end of the experiment. The plants from BSG and bBSG amended pots had number of leaves 1.21- and 1.14-times higher, respectively, than plants cultivated on control pots, although all treatments did not have any significant difference among each other. Regarding the yield, bBSG amended pots showed the highest fresh weight and their yield was 1.26-fold higher than control pots, followed by BSG amended pots, whose yield was 1.18-time higher than CTP. The application of biomasses also significantly increased the dry weight of plants with respect to CTP. In fact, BSG and bBSG treated escaroles showed a dry weight 1.19- and 1.24-fold higher than CTP, respectively.

No difference in the content of micronutrients and phosphorus were observed among plants grown in control soil or soils treated with BSG or bBSG, as reported in Table 4. Whereas, chlorophyll content of escarole leaves, initially unaffected by the treatments, from the 27th day after transplantation, was significantly higher in leaves from plants grown in treated soils, with respect to the control pots (Figure 2). However, no significant difference was observed between the bioprocessed and native BSG tested.

Discussion

Most of the BSG generated is used as feed or disposed of as landfill, whereas a little part of it is used for biogas/bioethanol production (Mussatto et al., 2006), nevertheless, up-cycling strategies that include its complete reutilization without further generation of by-products should be favored. Due to the potential health benefits deriving from its components, the inclusion of BSG in bakery products has been proposed by several authors (for a review see Lynch et al., 2016) and examples of such products can also be found at retail level. Since the incorporation of untreated BSG often entails negative repercussion on the structure of such products, BSG valorization as functional food ingredient, through bioprocessing technology, has also been recently proposed (Verni et al., 2020; Schettino et al., 2021; Koirala et al., 2022), while its the use as soil amendment is uncommon and it has been only partially investigated. The use of BSG as organic amendment in soils cultivated with maize was first proposed by Mbagwu and Ekwealor (1990). They found that the highest BSG

TABLE 1 Chemical and physicochemical characteristics of native (BSG) and bioprocessed brewers' spent grains (bBSG).

	pH	EC (dS m^{-1})	OC (%)	TN (%)	C/N	*P* (mg kg^{-1})	Moisture (%)
BSG	4.49 ± 0.15[a]	0.27 ± 0.04[b]	44.5 ± 8.0	3.46 ± 0.22	12.79 ± 2.99	6,359 ± 350[a]	84.36 ± 0.48
Bbsg	3.75 ± 0.11[b]	0.37 ± 0.04[a]	32.3 ± 1.3	3.60 ± 0.27	8.96 ± 0.30	4,113 ± 199[b]	83.23 ± 2.50
HSD.test	**	***	ns	ns	Ns	***	ns

Data are the means of three independent experiments ± standard deviations ($n = 3$).
[a−b]Values in the same column, among cultivated or uncultivated pots data groups, followed by a different letter, are significantly different according to HSD. test. ** Significant at $p \leq 0.01$, *** Significant at $p \leq 0.001$. *ns*, not significant.

TABLE 2 Chemical and physicochemical properties of soils unamended (CT) and amended with native (BSG) or bioprocessed brewers' spent grain (bBSG), uncultivated (A) or cultivated with escarole plants (P).

	pH_{H2O}	pH_{KCl}	EC (µS cm^{-1})	OC (g kg^{-1})	TN (g kg^{-1})	P_{ava} (mg kg^{-1})
			Pots without plant			
T0	8.71 ± 0.04[a]	7.65 ± 0.03	707 ± 264	8.04 ± 1.46[b]	1.27 ± 0.07[c]	3.43 ± 2.15
CTA	8.41 ± 0.07[b]	7.66 ± 0.03	700 ± 107	8.74 ± 1.74[b]	1.26 ± 0.03[bc]	2.31 ± 0.06
BSGA	8.12 ± 0.10[c]	7.54 ± 0.12	497 ± 113	14.03 ± 1.84[a]	1.69 ± 0.22[ab]	5.00 ± 2.20
bBSGA	8.19 ± 0.11[c]	7.53 ± 0.10	512 ± 100	15.01 ± 2.66[a]	1.79 ± 0.25[a]	5.12 ± 2.30
	*	ns	ns	**	**	ns
			Pots with plant			
T0	8.71 ± 0.04[a]	7.65 ± 0.03	707 ± 264	8.04 ± 1.46[b]	1.27 ± 0.07[b]	3.43 ± 2.15[ab]
CTP	8.37 ± 0.12[b]	7.69 ± 0.05	676 ± 89	10.53 ± 0.33[b]	1.29 ± 0.11[b]	2.43 ± 0.06[b]
BSGP	7.94 ± 0.09[c]	7.37 ± 0.16	557 ± 141	15.52 ± 2.12[a]	1.67 ± 0.15[a]	6.31 ± 1.50[ab]
bBSGP	7.83 ± 0.07[c]	7.52 ± 0.19	486 ± 40	17.11 ± 2.38[a]	1.67 ± 0.18[a]	6.62 ± 1.70[a]
	***	ns	ns	***	**	*

Data are the means of three independent experiments ± standard deviations ($n = 3$).
[a−c]Values in the same column, followed by a different letter, are significantly different according to HSD. test. *Significant at $p \leq 0.05$; **Significant at $p \leq 0.01$; ***Significant at $p \leq 0.01$; *ns*, not significant.

TABLE 3 Biometric features of escarole plants, grown in soil unamended (CTP) and amended with native (BSG) or bioprocessed brewers' spent grain (bBSG), at the end of the trial.

	Number of leaves per plant	Treated/CTP leaves ratio	Average head escarole fresh weight (g)	Treated/CTP yield ratio	Average head escarole dry weight (g)	Treated/CTP dry weight ratio
CTP	14 ± 1.2	-	124.4 ± 17.1[b]	-	25.2 ± 0.5[b]	-
BSGP	17 ± 1.5	1.21 ± 0.20	146.3 ± 3.3[ab]	1.18 ± 0.16	30.0 ± 0.7[a]	1.19 ± 0.08
bBSGP	16 ± 3.5	1.14 ± 0.23	156.9 ± 5.7[a]	1.26 ± 0.15	31.2 ± 1.2[a]	1.24 ± 0.11
	ns	ns	*	ns	*	ns

Data are the means of three independent experiments ± standard deviations ($n = 3$). [a,b]Values in the same column, followed by a different letter, are significantly different according to HSD. test.; *Significant at $p \leq 0.05$; *ns*, not significant.

dose (10% w/w) determined the better soil conditions due to its capacity to improve aggregate stability and water retention capacity, whereas the lowest dose (2.5% w/w) determined the highest crop production yield. Aboukila et al. (2018) tested BSG in comparison to compost in calcareous soils cultivated with squash. Authors concluded that the application of BSG was more economical than compost and determined the best results in terms of soil pH reduction, soil water holding capacity and squash yield. No further studies have been conducted with the use of BSG as soil amendment, while in a recent review, Chetrariu and Dabija (2020) reported the use of BSG for obtaining a biochar to employ as nutrient supplier for plant growth and soil improver.

On the other hand, LAB can regulate the fate of phosphate in soil (Levering et al., 2012) or fix atmospheric nitrogen (Giassi et al., 2016), can act as biocontrol agent and increase the shelf life of the amendment (Cacace et al., 2022), therefore their use in agriculture is desirable.

TABLE 4 Micronutrients and phosphorous content expressed as mg kg^{-1} of escarole leaves grown in soil unamended (CTP) and amended with native (BSG) or bioprocessed brewers' spent grain (bBSG).

	Mn	Fe	Cu	P
CTP	0.73 ± 0.09	12.93 ± 6.56	0.18 ± 0.06	141 ± 32.25
BSGP	0.98 ± 0.46	13.90 ± 7.44	0.18 ± 0.03	141 ± 9.32
bBSGP	0.71 ± 0.23	9.49 ± 7.55	0.15 ± 0.03	126 ± 6.13
	ns	ns	ns	ns

Data are the means of three independent experiments ± standard deviations ($n = 3$). *Ns*, not significant.

Bioprocessing of the biomass is crucial to enable higher microbial stability of the spent grain while leading to the synthesis/release of compounds of interest. Indeed, the significant lower pH of bBSG compared to that of BSG, ascribed to the higher content of lactic and acetic acids and, to a lesser extent, to hydroxycinnamic acids released by the enzymatic treatment (Verni et al., 2020), prevented the proliferation of other microorganisms, either bacteria or molds, potentially spoiling the biomass. The great impact of the bioprocessing on the biomass shelf-life is an aspect particularly appealing in view of the potential large-scale application of brewers' spent grain as soil amendment. In addition, as previously reported, the sequential enzymatic/fermentative treatment also enabled the release of peptides having higher hydrophobic ratio than those in BSG, a feature that enhances their solubility in lipids, thus facilitating access to hydrophobic radical species and to hydrophobic polyunsaturated fatty acids (Sarmadi and Ismail, 2010; Verni et al., 2020). On the downside, bioprocessing determined a 70% decrease of FAA most likely metabolized by the LAB used as starter.

The partial mineralization of BSG, operated by microorganisms during the bioprocessing, could have determined the release of salts causing a slight but significant increase of the EC of bBSG compared to BSG. Further, the lower content of total P in bBSG compared to BSG was probably due to the interaction of phosphates with the surface and the stirrer of the bioreactor during the bioprocessing, leading to a certain removal of that nutrient from the biomass.

The biomasses slightly but significantly decreased the soil pH. In addition, soil in cultivated pots showed lower pH values than uncultivated soils, thus highlighting the plant rhizosphere contribution to the soil pH level. As expected, biomasses addition to the soil led to significantly higher content of OC and TN in treated soils compared to the unamended ones, regardless of the plant presence. The P_{ava} content did not differ among pots without plants, even if the treated but uncultivated pots (BSGA and bBSGA) showed slightly (but not significantly) higher values of such parameter than the corresponding control (CTA). bBSG supplied less total P than BSG, but the P_{ava} content of the corresponding amended soils was similar. This is possibly due to the abundant monocarboxylic acids production of the *L. plantarum* strains used as starter for bioprocessing, that could promote the solubilization of P. It is indeed generally accepted that P solubilization is also associated with the release of low molecular weight organic acids which, through their hydroxyl and carboxyl groups, chelate the cations bound to phosphate, thus converting it into soluble forms (Tabatabai, 1994). In contrast, the rhizosphere effect of the escarole roots induced a significantly higher availability of phosphate in cultivated pots (BSGP and bBSGP), probably due to the release of more suitable di- and tri-carboxylic organic acids and phosphatases (Brunetti et al., 2019). In any case, all treatments shared a very low P_{ava} content (lower than 6.6 mg kg^{-1}) that could have represented a limiting factor for the crop.

The first 25 days after transplantation were possibly needed for the rooting and establishment of the plants while, after this period, both BSG and bBSG supported similarly the crop due to their almost equal N contribution to the plant nutrition. Although the number of leaves did not differ among treatments, their fresh and dry weight was different, leading to the highest final yield when bBSG amendment was applied. The dry weight of escaroles was influenced by the application of biomasses since all treatments received the same amount of water during irrigations, but the amended pots retained more water precisely because of the organic amendments. The higher availability of water provided a better photosynthesis, as confirmed also by the SPAD readings, thus a greater accumulation of photosynthates. Nevertheless, other cultivars or crops could respond differently to the same treatments due to their different genotypes, hence more studies should be performed. It can be hypothesized that the bioprocessing played an important promotion of the decomposition and mineralization processes of BSG and/or stimulating PGPM of the rhizosphere microbial community. A great deal of this stimulation might be due the organic acids produced, during the bioprocessing, by the carbohydrates metabolism of *L. plantarum* PU1. Indeed, it was recently showed that lactic, oxalic, and citric acids are used as source of carbon and energy by soil microorganisms, confirmed by the increase in dehydrogenase and phosphatase activity (Macias-Benitez et al., 2020), bioindicator of soil fertility and phosphate bioavailability (Karaca et al., 2010; Navnage et al., 2018). Treating soils with organic acids, especially lactic acid, not only affects soil physicochemical performances but also induces changes in the soil microbiota composition favoring the proliferation of microorganisms (*Bacillus* spp. and *Micrococcaceae*) involved in soil degradation and fertility (Macias-Benitez et al., 2020). The authors observed that, once the lactic acid was degraded, although the biodiversity tended to return to phyla similar to those found before the treatment, an induction pattern of PGPM was left (Macias-Benitez et al., 2020).

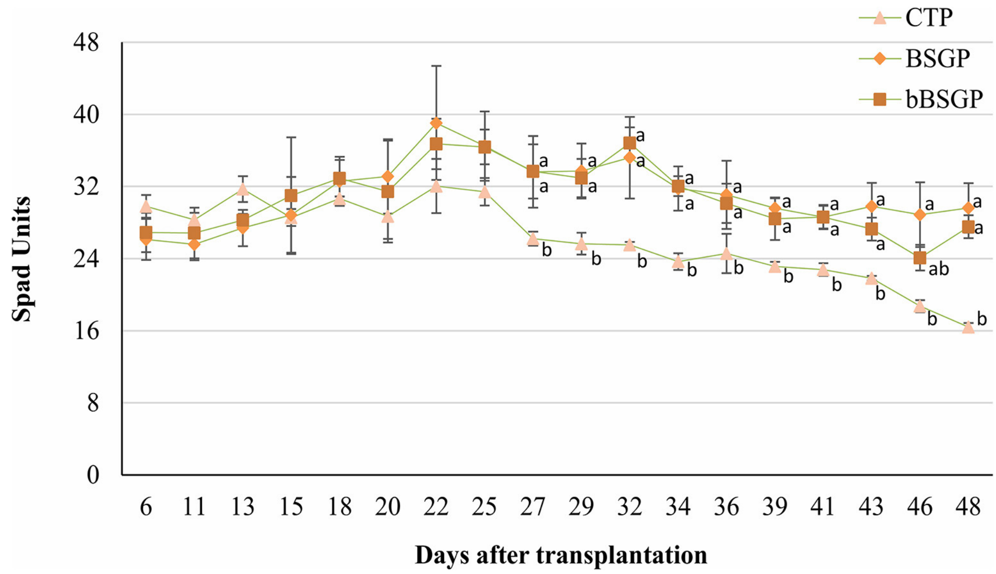


FIGURE 2
Effect of the biomasses on chlorophyll content of escaroles grown in control soil (CTP), soil amended with native (BSGP) or bioprocessed brewers' spent grain (bBSGP). [a,b]Different letters indicate significant differences among the data according to HSD test. Vertical bars represent standard deviation.

The similar P content found in leaves from all treatments is probably due to the low availability of such nutrient in the soils, while the similar content of Cu, Fe and Mn in leaves can be ascribed to their nature as micronutrients (even their level in control soil satisfied the plant nutrition). Although similar biometric parameters of escarole plants were found between amended and unamended soils, from the 27th day of treatment onward, BSG and bBSG prompted to a better chlorophyll content compared to unamended soils. Such effect, most likely caused by the higher TN content of amended soils, was similar to that previously found in escarole cultivated in soil amended with wasted bread, used as such or bioprocessed with amylolytic enzymes and lactic acid bacteria (Cacace et al., 2022).

Generally, the application of plant- or animal-based organic amendment residues is known to increase soil enzymatic activities with a crucial role in C (β-glucosidase and β-galactosidase), N (urease), P (phosphatases), and S (sulphatase) cycles and are also used as quality indicators for pollution, ecosystem perturbations, and agricultural practice (Karaca et al., 2010). Still, the contribution of microbial enzymes brought about by bBSG cannot be excluded as a factor influencing soil biochemical and microbial properties. As a matter of fact, during BSG bioprocessing, the environmental pressure exerted by the low availability of energy sources shifts *L. plantarum* phenotype toward the metabolism of arabinose and xylose and increases the expression of genes encoding for cellobiose metabolism (Acin-Albiac et al., 2022), all of which could be of great importance in the degradation of fibrous material in soil as well as the ability of the strain to adapt to soil conditions and keep exerting beneficial functions long after amendment practice. Moreover, the intense metabolic activity of β-glucosidases, whose genes are present in high redundance in LAB genomes, has been negatively correlated with soil heavy metals (Karaca et al., 2010) suggesting that these enzymes, involved in the degradation of carbohydrates as well as in the release of a wide range of phenolic compounds in BSG (Acin-Albiac et al., 2022), might be a key element to fight soil pollutants.

In conclusion, the use of brewers' spent grains as soil amendment determined higher yield of escarole compared to the unamended soil, especially when the biomass was previously subjected to bioprocessing. Overall, brewers' spent grains supplied organic matter and total nitrogen to soils, improving their fertility. The acidic nature of this biomass, especially when subjected to lactic acid fermentation, can improve alkaline soils increasing the solubility of nutrients. In contrast, the use of these biomasses is not recommended in acid soils, because can determine an excessive availability of potentially toxic elements and an excessive presence of Al deriving from mineral weathering. Although further investigation on the agronomical responses of other cultivars or plants, as well as LAB survival in amended soil, their ability to modulate soil microbiota, or their potential in chelating heavy metals or other soil pollutant are needed, the results collected in this preliminary study encourage its application for agricultural purpose, also solving the problem of disposing of such residues widely produced all over the world.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CGR, CCo, and GB contributed to the conception and design of the study. CCa and MV performed the laboratory analyses. AT and FD conducted the samplings and participated in the analysis. CCa wrote the first draft of the manuscript and CGR, CCo, MV, RC, and EP revised it. All authors contributed to manuscript revision, read, and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

AACC (2010). *Approved methods of the American Association of Cereal Chemistry, 11th edn.* St. Paul, MN: AACC.

Abdeldaym, E. A., Traversa, A., Cocozza, C., and Brunetti, G. (2018). Effects of a 2-year application of different residual biomasses on soil properties and potato yield. *Clean* 46, 1800261. doi: 10.1002/clen.201800261

Abdelrahman, H., Cocozza, C., Olk, D. C., Ventrella, D., Montemurro, F., and Miano, T. (2020). Changes in labile fractions of soil organic matter during the conversion to organic farming. *J. Soil Sci. Plant Nutr.* 20, 1019–1028. doi: 10.1007/s42729-020-00189-y

Aboukila, E. F., Nassar, I. N., Rashad, M., Hafez, M., and Norton, J. B. (2018). Reclamation of calcareous soil and improvement of squash growth using brewers' spent grain and compost. *J. Saudi Soc. Agric. Sci.* 17, 390–397. doi: 10.1016/j.jssas.2016.09.005

Acin-Albiac, M., Filannino, P., Coda, R., Rizzello, C. G., Gobbetti, M., and Di Cagno, R. (2022). How water-soluble saccharides drive the metabolism of lactic acid bacteria during fermentation of brewers' spent grain. *Microb. Biotechnol.* 15, 915–930. doi: 10.1111/1751-7915.13846

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements—FAO Irrigation and Drainage Paper 56*. Rome: FAO.

Ameen, F. A., Hamdan, A. M., and Moustafa, Y. E. (2020). Assessment of the heavy metal bioremediation efficiency of the novel marine lactic acid bacterium, *Lactobacillus plantarum* MF042018. *Sci. Rep.* 10, 314. doi: 10.1038/s41598-019-57210-3

Bianco, A., Budroni, M., Zara, S., Mannazzu, I., Fancello, F., and Zara, G. (2020). The role of microorganisms on biotransformation of brewers' spent grain. *Appl. Microbiol. Biotechnol.* 104, 8661–8678. doi: 10.1007/s00253-020-10843-1

Brunetti, A., Traversa, A., De Mastro, F., and Cocozza, C. (2019). Short term effects of synergistic inorganic and organic fertilization on soil properties and yield and quality of plum tomato. *Sci. Hortic.* 252, 342–347. doi: 10.1016/j.scienta.2019.04.002

Cacace, C., Rizzello, C. G., Brunetti, G., Verni, M., and Cocozza, C. (2022). Reuse of wasted bread as soil amendment: bioprocessing, effects on alkaline soil and escarole (*Cichorium endivia*) production. *Foods* 11, 189. doi: 10.3390/foods11020189

Chetrariu, A., and Dabija, A. (2020). Brewer's spent grains: possibilities of valorization, a review. *Appl. Sci.* 10, 5619. doi: 10.3390/app10165619

Church, F. C., Swaisgood, H. E., Porter, D. H., and Catignani, G. L. (1983). Spectrophotometric assay using o-phthaldialdehyde for determination of proteolysis in milk and isolated milk proteins. *J. Dairy Sci.* 66, 1219–1227. doi: 10.3168/jds.S0022-0302(83)81926-2

Ciavatta, C., Antisari, L. V., and Sequi, P. (1989). Determination of organic carbon in soils and fertilizers. *Commun. Soil Sci. Plant Anal.* 20, 759–773. doi: 10.1080/00103628909368115

Cocozza, C., and Ercolani, G. L. (1997). Siderophore production and associated characteristics in rhizosphere and non-rhizosphere flourescent pseudomonads. *Ann. Microbiol.* 47, 17–28.

De Pasquale, I., Verni, M., Verardo, V., Gómez-Caravaca, A. M., and Rizzello, C. G. (2021). Nutritional and functional advantages of the use of fermented black chickpea flour for semolina-pasta fortification. *Foods* 10, 182. doi: 10.3390/foods10010182

De Vos, B., Lettens, S., Muys, B., and Deckers, J. A. (2007). Walkley–Black analysis of forest soil organic carbon: recovery, limitations and uncertainty. *Soil Use Manag.* 23, 221–229. doi: 10.1111/j.1475-2743.2007.00084.x

Giassi, V., Kiritani, C., and Kupper, K. C. (2016). Bacteria as growth – promoting agents for citrus rootstocks. *Microbiol. Res.* 190, 46–54. doi: 10.1016/j.micres.2015.12.006

IUSS Working Group WRB (2015). "World Reference Base for Soil Resources," in *International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. World Soil Resources Reports No. 106 (Rome: FAO).

Karaca, A., Cetin, S. C., Turgay, O. C., and Kizilkaya, R. (2010). "Soil enzymes as indication of soil quality," in *Soil enzymology* ed. G. Shukla, A. Varma (Berlin: Springer), pp. 119–148.

Kargar, S. H. M., and Shirazi, N. H. (2020). *Lactobacillus fermentum* and *Lactobacillus plantarum* bioremediation ability assessment for copper and zinc. *Arch. Microbiol.* 202, 1957–1963. doi: 10.1007/s00203-020-01916-w

Koirala, P., Costantini, A., Maina, H. N., Rizzello, C. G., Verni, M., Beni, V. D., et al. (2022). Fermented brewers' spent grain containing dextran and oligosaccharides as ingredient for composite wheat bread and its impact on gut metabolome *in vitro*. *Fermentation* 8, 87. doi: 10.3390/fermentation,8100487

Lamont, J. R., Wilkins, O., Bywater-Ekegärd, M., and Smith, D. L. (2017). From yogurt to yield: Potential applications of lactic acid bacteria in plant production. *Soil Biol. Biochem.* 111, 1–9. doi: 10.1016/j.soilbio.2017.03.015

Levering, J., Musters, M. W. J. M., Bekker, M., Bellomo, D., Fiedler, T., de Vos, W. M., et al. (2012). Role of phosphate in the central metabolism of two lactic acid bacteria—a comparative systems biology approach. *FEBS J.* 279, 1274–1290. doi: 10.1111/j.1742-4658.2012.08523.x

Lynch, K. M., Steffen, E. J., and Arendt, E. K. (2016). Brewers' spent grain: a review with an emphasis on food and health. *J. Inst. Brewing* 122, 553–568. doi: 10.1002/jib.363

Macias-Benitez, S., Garcia-Martinez, A. M., Caballero Jimenez, P., Gonzalez, J. M., Tejada Moral, M., and Parrado Rubio, J. (2020). Rhizospheric organic acids as biostimulants: monitoring feedbacks on soil microorganisms and biochemical properties. *Front. Plant Sci.* 11, 633. doi: 10.3389/fpls.2020.00633

Mbagwu, J. S. C., and Ekwealor, G. C. (1990). Agronomic potential of brewers' spent grains. *Biol. Wastes* 34, 335–347. doi: 10.1016/0269-7483(90)90034-P

Mininni, C., Grassi, F., Traversa, A., Cocozza, C., Parente, A., Miano, T., et al. (2015). *Posidonia oceanica* (L.) based compost as substrate for potted basil production. *J. Sci. Food Agric*. 95, 2041–2046. doi: 10.1002/jsfa.6917 https://doi.org/10.1002/jsfa.6917

Mussatto, S. I., Dragone, G., and Roberto, I. C. (2006). Brewers' spent grain: generation, characteristics and potential applications. *J. Cereal Sci*. 43, 1–14. doi: 10.1016/j.jcs.2005.06.001

Navnage, N. P., Patle, P. N., and Ramteke, P. R. (2018). Dehydrogenase activity (DHA): measure of total microbial activity and as indicator of soil quality. *Int. J. Chem. Stud* 6, 456–458.

Olsen, S. R. (1954). *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate* (No. 939). Washington, DC: US Department of Agriculture.

Ozores-Hampton, M., Stansly, P. A., and Salame, T. P. (2011). Soil chemical, physical, and biological properties of a sandy soil subjected to long-term organic amendments. *J. Sustain. Agric*. 35, 243–259 doi: 10.1080/10440046.2011.554289

Ravindran, R., and Jaiswal, A. K. (2016). Exploitation of food industry waste for high-value products. *Trends Biotechnol*. 34, 58–69. doi: 10.1016/j.tibtech.2015.10.008

Rizzello, C. G., Nionelli, L., Coda, R., De Angelis, M., and Gobbetti, M. (2010). Effect of sourdough fermentation on stabilisation, and chemical and nutritional characteristics of wheat germ. *Food Chem*. 119, 1079–1089. doi: 10.1016/j.foodchem.2009.08.016

Sarmadi, B. H., and Ismail, A. (2010). Antioxidative peptides from food proteins: a review. *Peptides* 31, 1949–1956. doi: 10.1016/j.peptides.2010.06.020

Schettino, R., Verni, M., Acin-Albiac, M., Vincentini, O., Krona, A., Knaapila, A., et al. (2021). Bioprocessed brewers' spent grain improves nutritional and antioxidant properties of pasta. *Antioxidants* 10, 742. doi: 10.3390/antiox10050742

Sparks, D. L., Page, A. L., Helmke, P. A., Loeppert, R. H., Soltanpour, P. N., Tabatabai, M. A., et al. (1996). "Methods of soil analysis," in *Chemical Methods*. (Madison, WI: SSSA Book).

Sposito, G. (2016). *The Chemistry of Soils*. Oxford: Oxford University Press.

Tabatabai, K. A. K. (1994). Effect of organic acids on release of phosphorus from phosphate rocks. *Soil Sci*. 158, 442–453.

Trinchera, L., Leita, P., and Sequi, P. (2006). *Metodi di Analisi per I Fertilizzanti*. Roma : Ministero delle Politiche Agricole Alimentari e Forestali.

Verni, M., Pontonio, E., Krona, A., Jacob, S., Pinto, D., Rinaldi, F., et al. (2020). Bioprocessing of brewers' spent grain enhances its antioxidant activity: characterization of phenolic compounds and bioactive peptides. *Front. Microbiol*. 11, 1831. doi: 10.3389/fmicb.2020.01831

Verni, M., Rizzello, C. G., and Coda, R. (2019). Fermentation biotechnology applied to cereal industry by-products: nutritional and functional insights. *Front. Nutr*. 6, 42. doi: 10.3389/fnut.2019.00042

Weiss, W., Vogelmeier, C., and Görg, A. (1993). Electrophoretic characterization of wheat grain allergens from different cultivars involved in bakers' asthma. *Electrophoresis* 14, 805–816. doi: 10.1002/elps.11501401126

Yoo, J. H., Luyima, D., Lee, J. H., Park, S. Y., Yang, J. W., An, J. Y., et al. (2021). Effects of brewer's spent grain biochar on the growth and quality of leaf lettuce (*Lactuca sativa* L. *var. crispa.). Appl. Biol. Chem*. 64, 10. doi: 10.1186/s13765-020-00577-z

Zhang, W., Xu, M., Wang, X., Huang, Q., Nie, J., Li, Z., et al. (2012). Effects of organic amendments on soil carbon sequestration in paddy fields of subtropical China. *J. Soils Sedim*. 12, 457–470. doi: 10.1007/s11368-011-0467-8

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 06 December 2022
DOI 10.3389/fsufs.2022.1005740

OPEN ACCESS

EDITED BY
Marzia Ingrassia,
Università degli Studi di Palermo, Italy

REVIEWED BY
Marga Lopez,
Universitat Politecnica de Catalunya, Spain
Sukron Romadhona,
University of Jember, Indonesia

*CORRESPONDENCE
Hupenyu Allan Mupambwa
hmupambwa@unam.na;
hamupambwa@gmail.com

SPECIALTY SECTION
This article was submitted to Waste Management in Agroecosystems, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 28 July 2022
ACCEPTED 15 November 2022
PUBLISHED 06 December 2022

CITATION
Katakula AAN, Gawanab W, Handura B, Itanna F and Mupambwa HA (2022) Seaweed (*Gracilariopsis funicularis*) biochar incorporation into a goat manure–food waste vermicompost for optimized vermidegradation and nutrient release.
Front. Sustain. Food Syst. 6:1005740.
doi: 10.3389/fsufs.2022.1005740

Seaweed (*Gracilariopsis funicularis*) biochar incorporation into a goat manure–food waste vermicompost for optimized vermidegradation and nutrient release

Asteria Aili Ndiipohamba Katakula[1,2], Werner Gawanab[3], Bethold Handura[1], Fisseha Itanna[4,5] and Hupenyu Allan Mupambwa[1]*

[1]Sam Nujoma Marine and Coastal Resources Research Center, University of Namibia, Henties Bay, Namibia, [2]Department of Crop Production and Agricultural Technologies, University of Namibia, Oshakati, Namibia, [3]Agriculture Laboratory (Nutrition Section), Ministry of Agriculture Water and Forestry, Windhoek, Namibia, [4]Department of Soil Science and Resource Conservation, Faculty of Agriculture, National University of Lesotho, Maseru, Lesotho, [5]School of Interdisciplinary Research and Graduate Studies, College of Graduate Studies, University of South Africa, Pretoria, South Africa

Vermicomposts are organic fertilizer sources that are being promoted; however, their concentrations of macronutrients such as NPK are very low. This study, therefore, evaluated the effects of amending goat manure–food waste mixture with biochar prepared from seaweed (*Gracilariopsis funicularis*) at 0% (control), 2, 4, 6, and 8% on vermicompost degradation and macronutrient release. After 10 weeks of vermicomposting, the highest pH of 9.06 was observed within the control, whilst the lowest was 8.7 in the 8% treatment. The electrical conductivity showed a positive relationship with the level of biochar incorporation with the highest of 16.5 mS/cm from the 8% treatment, whilst the lowest was within the control with 6 mS/cm. There were no significant differences between treatments on humification parameters; however, there were significant differences in the changes in a C/N ratio with the final C/N ratio of 14.4, 14.9, 16.7, 15.1, and 14.4 for the control, 2, 4, 6, and 8% treatments, respectively. A higher incorporation rate resulted in the higher concentration of potassium with a value of 32.3 g/kg at week 8. The final percentage change in Olsen P was 19, 14.2, 7.3, 4.1, and 3.0% for the 8%, 6%, control, 4%, and 2% treatments, respectively. An optimized level of 6% to 8% biochar incorporation ratio can be recommended. However, the incorporation of *G. funicularis* biochar does not seem to influence changes in the vermidegradation efficiency, though it can significantly improve the macronutrients such as P, K, and Mg concentrations as well as the macroelement concentrations.

KEYWORDS

biodegradation, compost maturity, *Eisenia fetida*, nutrient release, seaweed biochar

Introduction

The advent of the green revolution saw the introduction of huge industrialization and intensification of agricultural activities, which has generated huge quantities of waste materials (Chen et al., 2020). Furthermore, the application of inorganic fertilizers to increase yields of crops has resulted in increased crop yield though this has also contributed to soil degradation as these fertilizers only feed the crop, not the soil, which is a living ecosystem. Traditionally, composts have been used as organic sources of nutrients, with their limitations being the slow release of nutrients into the soil coupled with low nutrient levels and the probability of introducing potentially toxic pathogens and heavy metals into the environment (Chen et al., 2020). Recently, research has focused on improved organic fertilizers in sustainable agriculture such as vermicomposts which involve the use of solid organic materials such as food waste, animal waste, and sewage sludge processed using earthworms such as *Eisenia fetida* and other species (Mupambwa et al., 2022).

Though both composts and vermicomposts are being promoted as nutrient sources, they are still inferior in nutrition when compared with inorganic fertilizers; hence, farmers always prefer to use inorganic fertilizers regardless of their limited soil health benefits. For example, urea has 46% nitrogen, compound fertilizer like 3:2:3 (35%) has 42.8% phosphorus and 28% potassium, whilst homemade compost was reported to have as low as 0.5% nitrogen, 0.27% phosphorus, and 0.81% potassium. This has led researchers to use various materials for amendment such as fly ash, rock phosphate, and biochar as well as other methods such as phosphorus-solubilizing bacteria to increase nutrient content. A study by Zheng et al. (2020) reported that the total and extractable phosphorus fractions increased, whilst loss of N was reduced during composting of sewage sludge mixed with bulking agents such as spent mushroom substrate. According to Lukashe et al. (2019), the inoculation of fly ash–cow dung-based vermicompost with phosphate-solubilizing microbes accelerated the biodegradation resulting in improved vermicompost with low C/N ratio and high Olsen phosphorus. A study that used modified fly ash as an amendment to remediate heavy metal contamination from the soil reported that the mixture of fly ash and chicken manure reduced the concentrations of cadmium, copper, and lead by 49.0, 53.5, and 67.8%, respectively. They also observed an increase in organic matter and available NPK (Hu et al., 2021).

In another study, the incorporation of biochar made from corn cobs and wood enhanced the quality of soil as it supplied a more stable carbon source as well as essential plant nutrients during the production of maize (Kizito et al., 2019). Biochar as an amendment is quite interesting as it is rich in recalcitrant forms of carbon and contains elevated nutrient concentrations (Katakula et al., 2020). The use of biochar as an amendment of composting materials has the potential to increase organic matter content and reduce the bioavailability of heavy metals, whilst enhancing humification parameters and nutrient retention during vermicomposting (Were et al., 2019). Furthermore, the amendment with biochar enhances bioavailable nutrients in the soil and increases microbial action that drives soil biochemical processes which are critical in improving soil physical properties responsible for nutrient and water retention (Wang et al., 2020).

Research has shown that the amendment of 10% (w/w) plant biochar into kitchen waste–sewage sludge vermicompost increased the growth and multiplication of earthworms by up to 53.9% (Khan et al., 2019). In this same study, biochar amendments enhanced the bioavailability of nitrogen by up to 31%, phosphorus by 10%, and potassium by 17%. Similarly, Makini et al. (2020) reported that amending soils with vermicompost prepared from goat manure at a rate of 30t ha^{-1} resulted in higher soil pH, total N, and extractable P and K.

Much of the research that has used biochar as an amendment has mainly used a material of terrestrial origin with no research having used marine biomass. Recently, Katakula et al. (2020) identified that biochar derived from seaweed species such as *Laminaria pallida* and *Gracilariopsis funicularis* pyrolysed at a temperature of 400°C can generate nutrient-rich and carbon-rich biochar. Marine biomass derived-biochar can be an important source of amendment for organic fertilizers in hyper-arid countries such as Namibia. However, there is limited research that looked at marine biomass and converted them into biochar to be used as an amendment into vermicompost. Research that focuses on the use of waste materials such as animal manures, food waste, and seaweeds can be critical in circular economies as they are critical in waste beneficiation. Furthermore, unlike in uncontrolled decomposition of these wastes where the decomposition results in the loss of C, processes such as vermicomposting are also critical in carbon sequestration as they create materials that can bring back carbon into the soil. With this background, this study was guided by the objective of evaluating seaweed biochar incorporation into food waste–goat manure vermicompost for enhanced vermidegradation (carbon-to-nitrogen ratio, pH, and electrical conductivity) and nutrient mineralization (P, Ca, Na, Mg, and K).

Materials and methods

Source of materials utilized

The experiment was conducted at the University of Namibia's Sam Nujoma Campus, located in Henties Bay in the Erongo Region of Namibia. The optimum ratio of food waste and goat manure mixture of 50% food waste and 50% goat manure was used based on the results of Katakula et al. (2021). The seaweed biochar used in this study was identified from Katakula et al. (2020), and this was derived from *G.*

funicularis which was pyrolysed at a temperature of 400°C for 1 h. Vermireactors made from 20-L plastic buckets were used as outlined by Katakula et al. (2021). The characteristics of the food waste–goat manure and biochar used in this study can be found in Katakula et al. (2020, 2021). The earthworms were obtained from the local wormery at the University of Namibia's Sam Nujoma Campus, where the species *Eisenia fetida* was kept feeding on mainly vegetable food waste and goat manure.

Treatments, experimental design, and set-up

Seaweed biochar (SB) was incorporated into the optimized food waste–goat manure mixture (FWGM) at five different levels on a dry w/w basis, and this gave five treatment combinations, which are control (FWGM only), 2% SB + FWGM, 4% SB + FWGM, 6% SB + FWGM, and 8% SB + FWGM. These treatments were laid in a completely randomized design which were replicated three times. Following the preparation of the various treatments, these were allowed to pre-compost for 2 weeks before the addition of 25 g of earthworms (*E. fetida*) per kg of vermicompost as recommended by Mupambwa and Mnkeni (2016). A moisture content of 70–80% was maintained by lightly sprinkling the buckets with water, and these treatments were kept under a shade at room temperature. Non-destructive sampling was done for each treatment at 0, 4, 8, and 10 weeks. The collected vermicompost samples were air-dried and ground using a mechanical grinder (Polymix PX-MFC 90 D, Kinematica AG, Switzerland) for chemical characterization.

Electrical conductivity and pH

Electrical conductivity (EC) and pH were measured in water at a ratio of 1:10 (w/v) as described by Agri Laboratory Association of Southern Africa (AgriLASA) (2004). In brief, 5.g of the vermicompost was mixed with 50 mL of deionized water and shaken with a horizontally reciprocating shaker at 120 rpm for 30 min, and then, pH and EC were measured using a calibrated multimeter (Lovibond Water Testing, SensoDirect 150).

Olsen extractable P

The Olsen method was used to determine extractable phosphorus because it has been shown to be effective for acidic materials (Schoenau and O'Halloran, 2006). A solution of 0.5 M sodium hydrogen carbonate adjusted to a pH of 8.5 using 1 M of sodium hydroxide was used for extraction. In brief, 2.5 g of the vermicompost was shaken in 50 mL of the extracting solution for 30 min at 120 rpm and then filtered with Whatman No. 2 filter paper. The extracts were then analyzed for P using the ascorbic acid method as described by Kuo (1996).

Total C and N

Total C and N were determined using the dry combustion method employing a LECO CHN628 auto analyser (LECO Corporation, USA).

Extractable cations (Ca, Mg, Na, and K)

The cations were extracted using the ammonium acetate method as described by Agri Laboratory Association of Southern Africa (AgriLASA) (2004). A solution of 1 M ammonium acetate adjusted to pH 7 was used to extract the cations. To prepare this, an amount of 57 mL of glacial acetic acid was diluted with deionized water to a volume of 500 mL. An amount of 69 mL of concentrated ammonia solution was then added to the diluted solution of acetic acid. The solution was mixed well and diluted to about 900 mL with deionized water, and then, pH was adjusted to 7 using either acetic acid or ammonia solution. Five grams of vermicompost was placed in a 100-mL extraction bottle, 50 mL of ammonium acetate solution was added to the extraction bottle, and the mixture was shaken horizontally on a reciprocating shaker at 180 rpm for 30 min. The extracts were filtered using Whatman Number 2 filter paper, and the cation concentrations in the solution were determined using a calibrated inductively coupled plasma–optical emission spectrometer (ICP-OES—iCAP 6000 series).

Humification parameters

The humic and fulvic acid fractions in the vermicomposts were extracted using a method described by Sanchez-Monedero et al. (1996). A 0.1 mol L^{-1} NaOH solution was used at an extraction ratio of 2:40 (w/v) and shaken for 4 h with a reciprocal shaker. The extracts were then centrifuged at 4,000 rpm for 15 min. After centrifugation, the supernatant was divided into two fractions, with one half stored for analysis of the total extractable C fraction (*C*tEX). The other half was acidified to pH 2 by adding drops of concentrated H_2SO_4, to form a precipitate representing the humic acid (HA) fractions, whilst the liquid part represented the fulvic acid fraction. The acidified extracts were allowed to coagulate for 24 h at 4 °C and further centrifuged at 4,000 rpm to separate the humic and fulvic fractions. The non-precipitated part of the centrifuged samples was then further analyzed for fulvic acid carbon (CFA). The C concentrations in the supernatants were determined using the dichromate oxidation method, with the concentration of the humic acid (CHA) fraction being calculated as the difference between C_{tEX} and CFA. The humification ratio (HR, equation 1), humification index (HI, equation 2), percentage of humic acids (Pha, equation 3), and polymerization index (PI, equation 4), which are indices used for the evaluation of humification level in the vermicompost, were then calculated as indicated in the equations.

$$HR = \frac{C_{tEX}}{C} \times 100 \quad (1)$$

$$HI = \frac{C_{HA}}{C} \times 100 \quad (2)$$

$$Pha = \frac{C_{HA}}{C_{tEX}} \times 100 \quad (3)$$

$$PI = \frac{C_{HA}}{C_{FA}} \times 100 \quad (4)$$

Statistical analysis

The data were analyzed using repeated measures of analysis of variance (ANOVA). Where sphericity assumptions could not be met, the Greenhouse–Geisser correction of P was used. For the humification parameters, a one-way analysis of variance (ANOVA) was performed for the data collected at week 10. Mean separations were conducted using the Fisher's protected least significant at $P < 0.05$ when analysis of variance indicated a significant P-value. All data were analyzed using JMP version 14.0.0 statistical software (SAS Institute, Inc., Cary, North Carolina, USA, 2010), whilst all the graphs were plotted using Microsoft Excel (2007).

Results

Effects of seaweed biochar incorporation during vermicomposting on vermicompost maturity

pH and electrical conductivity

A significant difference ($P < 0.05$) was observed between treatments on changes in pH across the 10 weeks of vermicomposting (Table 1). The pH was alkaline throughout the vermicomposting process with pH increasing from the initial values across all treatments (Figure 1). After 10 weeks of vermicomposting, the control treatment which had no biochar incorporated into it had the highest pH of 9.06, whilst the lowest pH was 8.72 observed in the 8% biochar treatment. It was interesting to observe that the final pH values at 10 weeks showed a strong link to the level of biochar incorporation as it followed the order 0 >2 >6 >4 >8% biochar. After 10 weeks of vermicomposting, the pH values observed were 9.06, 8.83, 8.79, 8.82, and 8.72 for the 0, 2, 4, 6, and 8% treatments, respectively.

Throughout the 10 weeks of vermicomposting, EC showed an almost linear increase for all treatments, with a significant difference ($P < 0.05$) being observed between treatments and time as shown in Table 1 and Figure 2. Similar to the observations of pH, the higher the biochar incorporation rate, the higher the EC, and also, the higher the incorporation rate, the higher the rate of change (Figure 2). Across all treatments between 0 and 10 weeks, EC increased by 28, 42.2, 42.3, 54, and 67% for the 0, 2, 4, 6, and 8% treatments, respectively. After the 10 weeks of vermicomposting, the final EC values were 6, 9.2, 10.9, 12.4, and 16.5 mS/cm for the 0, 2, 4, 6, and 8% treatments, respectively.

C/N ratio

Across the different treatments, there were significant differences ($P < 0.05$) observed in changes in a C/N ratio, across the 10 weeks of vermicomposting (Table 1). Generally, across all treatments the C/N decreased from an average C/N of 34:1 at week 0 to a final average of 15:1 at week 10 (Figure 3). After the 10 weeks of vermicomposting, relative to the starting values, the C/N ratio decreased by 97, 116, 155, 128, and 134% for the 4, 6, 2, 8%, and control treatments, respectively, as indicated by the significant difference in time indicated in Table 1. At the end of the vermicomposting, the final C/N ratios were 14.4, 14.9, 16.7, 15.1, and 14.4 for the treatments 0, 2, 4, 6, and 8%, respectively. There were no significant interactions ($P > 0.05$) between treatments and time (Table 1).

Humification parameters

For all the four humification indices measured which are humification ratio (HR), humification index (HI), percentage of humic acids (Pha), and polymerization index (PI), there were no significant differences ($P > 0.05$) between all treatments after 10 weeks of vermicomposting. The highest humification ratio was observed in the control treatment with a humification ratio of 16.1, whilst the lowest was the 4% treatment with a HR of 13.8. The HR values followed the order 0 > 8 > 2 > 6 > 4% with final values of 16.1, 16.0, 15.6, 15.3, and 13.8 for biochar treatments, respectively (Figure 4A). For a humification index, the control treatment had the highest value of 2.8, whilst the lowest was with the 4% treatment with a HI of 2.3. The final HI after 10 weeks of vermicomposting followed the order of 4 < 6 < 2 < 8% < control (Figure 4B).

Similarly, the control treatment also resulted in the highest value of percentage of humic acids of 17.8, whilst the 6% treatment had the lowest Pha of 16.5. The Pha followed the order of 6 < 4% < 8 < 2% < control with 16.5, 16.7, 16.9, 17.1, and 17. 8, respectively (Figure 4C). For a polymerization index, the highest value was observed at the control treatment with a PI of 21.6, whilst the lowest was 19.9 at 6% biochar treatment. The PI followed the order of 6 < 4 <8 < 2% < control with 19.9, 20.1, 20.4, 20.6, and 21.6, respectively (Figure 4D).

TABLE 1 Repeated measures of ANOVA for changes in the selected parameters during vermicomposting of a goat manure–food waste mixture amended with seaweed (*G. funicularis*) biochar.

	Treatment		Time (weeks)		Treatments × time	
Parameter	*F*	*P*	*F*	*P*	*F*	*P*
C/N ratio	0.67	<0.0001	373.85	<0.0001	1.84	ns
pH	29.45	<0.0001	520.45	<0.0001	8.79	<0.0001
EC (mS/cm)	129.4	<0.0001	397.59	<0.0001	22.06	<0.0001
Olsen P (g/kg)	11.12	<0.0024	11.48	0.0010	1.42	ns
Ca (g/kg)	1.06	ns	110.14	<0.0001	14.15	<0.0001
K (g/kg)	887.06	<0.0001	42.62	<0.0001	67.71	<0.0001
Mg (g/kg)	3.80	0.0511	46.79	<0.0001	3.49	0.0167
Na (g/kg)	863.63	<0.0001	92.58	<0.0001	34.24	<0.0001

ns, not significant at P > 0.05; F and P represent the F statistic and P-value, respectively.

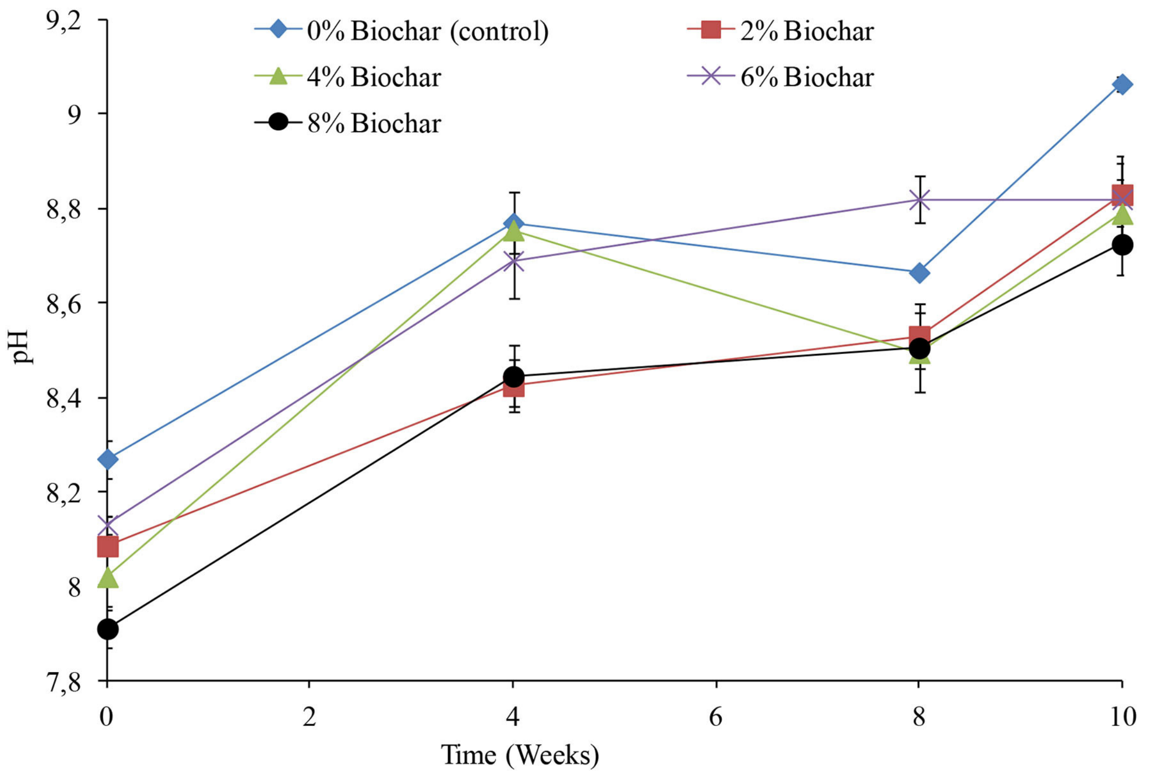


FIGURE 1
Changes in pH during vermicomposting of goat manure–food waste mixture amended with seaweed (*G. funicularis*) biochar. Error bars indicate standard deviation.

Effects of seaweed biochar incorporation during vermicomposting on nutritional content

Olsen extractable phosphorus

There were significant differences ($P < 0.05$) observed between treatments on changes in Olsen phosphorus as shown in the repeated measures of ANOVA (Table 1). The 8% treatment gave the highest final concentration of Olsen extractable phosphorus of 0.40 g per kg, whilst the 2% treatment had the lowest final concentration of 0.30 g per kg of vermicompost at 10 weeks. It was interesting to observe that the changes in Olsen P during vermicomposting could be modeled using a second-order polynomial equation with

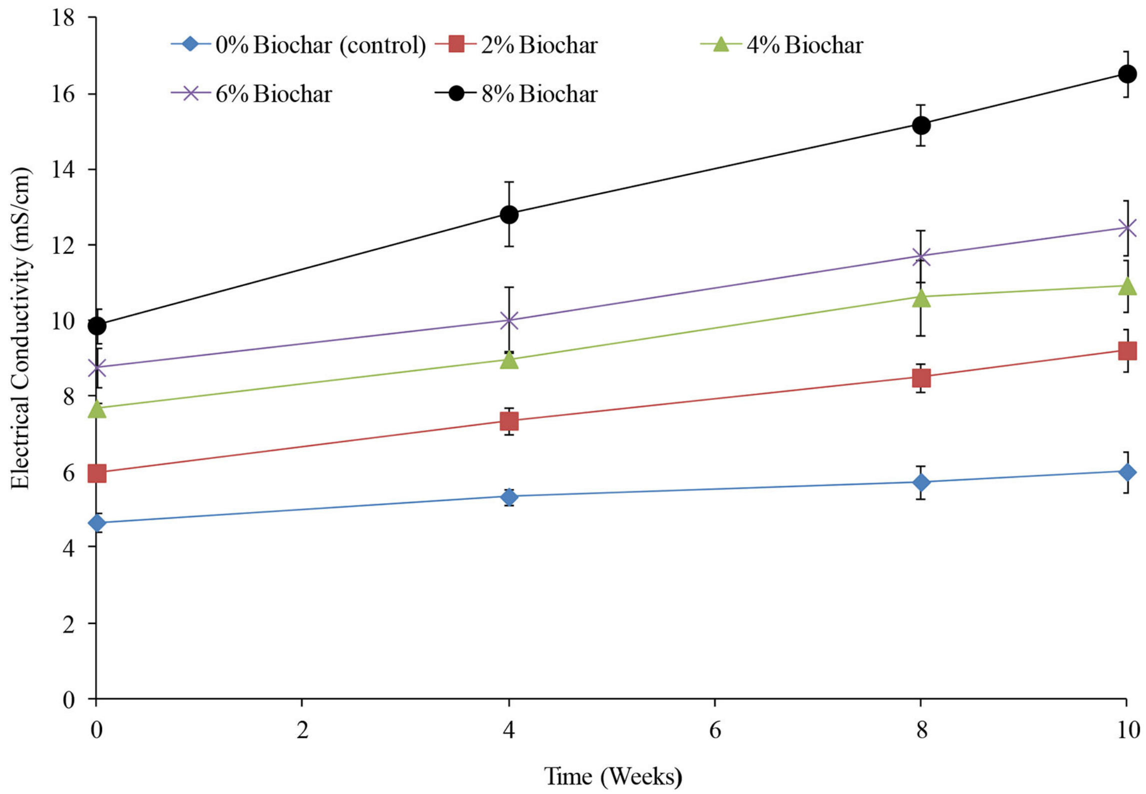


FIGURE 2
Changes in electrical conductivity during vermicomposting of goat manure–food waste mixture amended with seaweed (*G. funicularis*) biochar. Error bars indicate standard deviation.

very high R^2 values (Figure 5). For all treatments, the peak Olsen phosphorus was observed between week 6 and week 8 of vermicomposting, and after 8 weeks, almost all treatments started showing a decrease in Olsen P concentration. After 10 weeks of vermicomposting, the final percentage change in Olsen P was 19, 14.2, 7.3, 4.1, and 3.0% for the 8, 6, 0, 4, and 2% treatments, respectively (Figure 5).

For the control treatment, the peak concentration of Olsen P was observed at week 4 with a concentration of 0.37 g/kg which was a 7.3% increase in Olsen P compared with the initial concentration. The peak concentration of the 2% biochar treatment for Olsen P was observed at week 4 with a concentration of 0.38 g/kg with a 3.0 % increase. For the 4% treatment, the peak concentration of Olsen P was observed at week 8 with a concentration of 0.40 g/kg with a 4.1 % increase in Olsen concentration. The peak concentration of the 6% treatment was observed at week 4 with the Olsen concentration of 0.41 g/kg with a 14.2 % increase in Olsen P. For the 8% treatment, the peak Olsen concentration was 0.42 g/kg observed at week 8 with a 19% increase in Olsen P relative to the starting values (Figure 5).

Extractable cations (Ca, Mg, Na, and K)

There were significant differences ($P < 0.05$) observed between treatments for Mg, K, and Na except for Ca as shown in repeated measures of ANOVA (Table 1). For all treatments except for the control, the concentration of calcium increased from week 0 until week 8 and thereafter significantly decreased to concentrations that were below the original concentrations. However, the control treatment showed an almost constant concentration of calcium across the 10 weeks of vermicomposting. After 10 weeks of vermicomposting, the final concentration of calcium was observed to be high in the control followed by the 2, 4, 8, and 6% treatments with the final concentration of 18.9, 16.2, 15., 15.5, and 15.3 g/kg, respectively (Figure 6A). It was observed that the final concentration of calcium for all treatments was lower than that of the treatment without biochar.

Similar to the changes in electrical conductivity, the higher the concentration of biochar incorporation rate, the higher the concentration of potassium. For all treatments, the concentration was almost consistent across the 10 weeks of vermicomposting, whilst it increased only for the 8% biochar concentration (Figure 6B). The final concentration of potassium

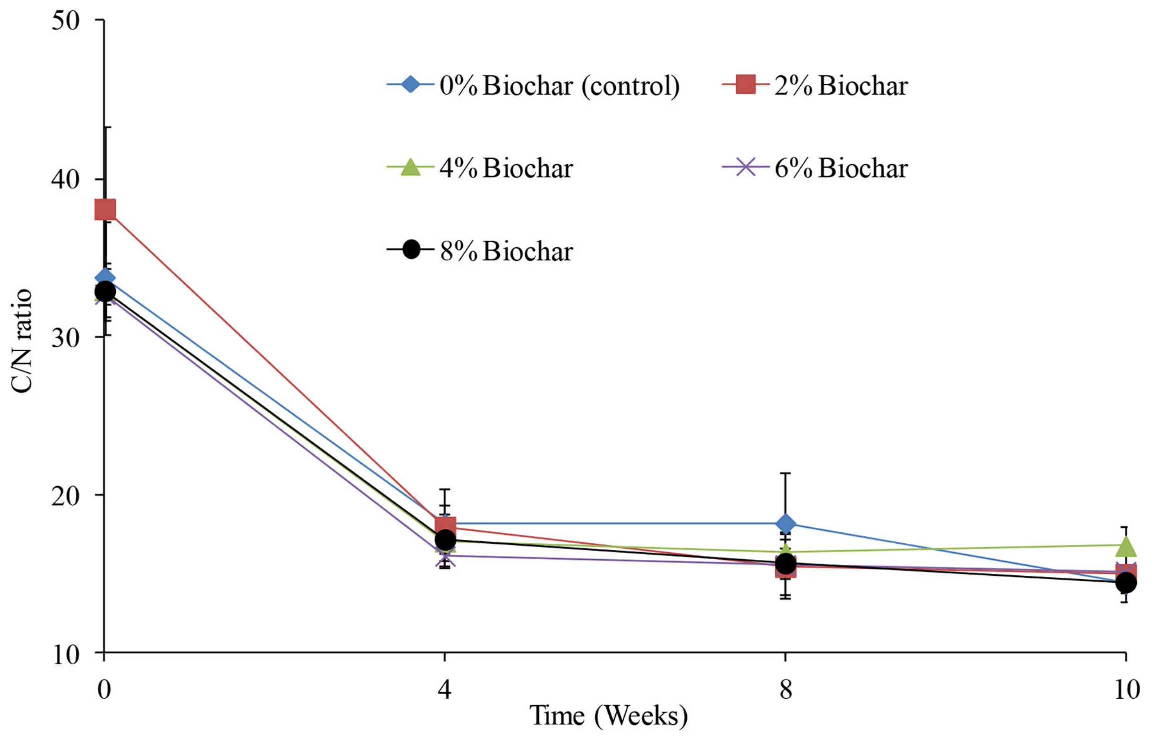


FIGURE 3
Changes in carbon-to-nitrogen ratio (C/N) during vermicomposting of a goat manure–food waste mixture amended with seaweed (*G. funicularis*) biochar into. Error bars indicate standard deviation.

followed the order 8 > 6 > 4 > 2 > 0% with the final concentration of 27.4, 15.8, 15.0, 14.1, and 6.4 g/kg after 10 weeks of vermicomposting. For all treatments, the concentration of magnesium increased until week 8 and thereafter decreased (Figure 6C). The final concentration of magnesium followed the order 0 > 2 > 4 > 8 > 6% with the final concentration of 0.59, 0.58, 0.58, 0.55, and 0.52 g/kg at 10 weeks (Figure 6C). Generally, sodium showed a small decrease for most of the treatments across the 10 weeks of vermicomposting. After 10 weeks, the higher the biochar incorporation rate, the higher the concentration of sodium. The final concentration of sodium followed the order 8 > 6 > 4 > 2 > 0% with the final concentration of 5.44, 3.45, 3.29, 3.2, and 2.2 g/kg at 10 weeks (Figure 6D).

Discussion

Influence of seaweed biochar incorporation on vermidegradation

According to the results of the study, the alkalinity of the pH is probably from the materials used which are goat manure and food waste which had a pH of 9 and not due to the application rate of biochar. The increase in pH across all treatments could be attributed to the release of ammonia and calcium as suggested by Karwal and Kaushik (2021), and this has been attributed to earthworm activity. Furthermore, the pH increase has also been reported to be attributed to the increase in ash formation and mineralization of organic nitrogen as a result of microbial activities (Jain et al., 2018). The alkaline vermicompost may present an opportunity to use it as an amendment for acidic soils though there is no clear link between the level of inclusion of biochar and the changes in pH. Though the pH was alkaline, it was still within the region where most of the macronutrients needed by the plants will still be bioavailable as recommended by Simms et al. (2020). In our study, it was clear that the higher EC observed is attributed to the level of biochar incorporation. The increase in EC is attributed to the high levels of cations mainly calcium and potassium that are present in the biochar; hence, the higher the biochar level, the higher the EC. Higher EC reflects the presence of more soluble salts, metabolites such as ammonium, and inorganic ions that are produced by earthworm's activities during vermicomposting (Lukashe et al., 2019). It will be critical to monitor the changes in electrical conductivity when seaweed biochar amended vermicompost is incorporated into the soil as the EC value of beyond 4 mS/m has been reported to result in soil salinity. The high salinity observed in the vermicomposts from the different treatments could mean that these vermicomposts may not be an appropriate amendment in the growing of saline-sensitive

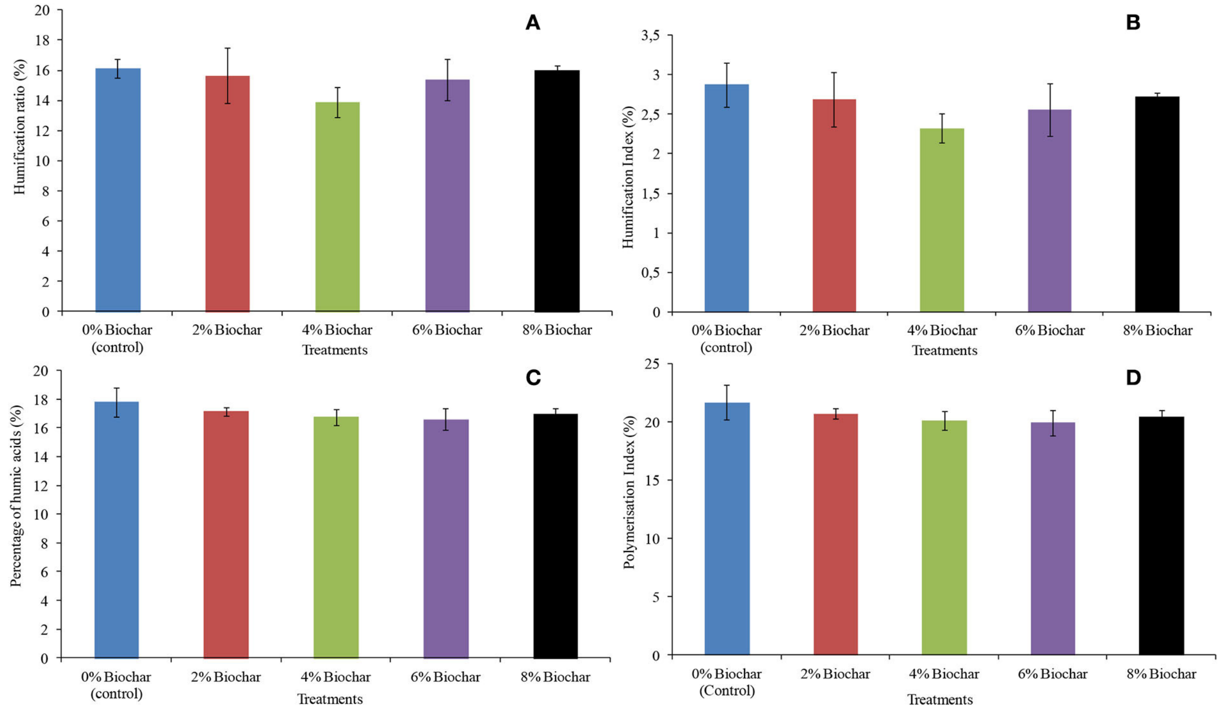


FIGURE 4
Final humification parameters after 10 weeks of vermicomposting of a goat manure–food waste mixture amended with seaweed (*G. funicularis*) biochar. **(A)** (Humification ratio); **(B)** (humification index); **(C)** (percentage of humic acids); and **(D)** (polymerization index).

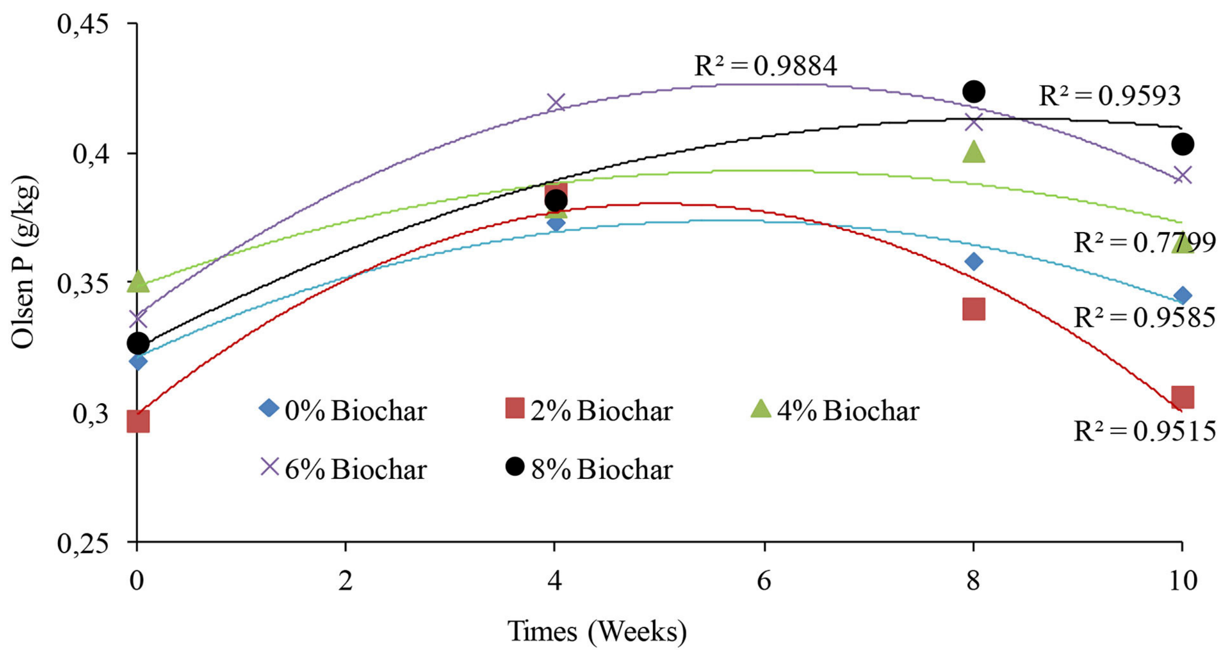


FIGURE 5
Second-order polynomial line graphs showing the trends of changes in Olsen P after 10 weeks of vermicomposting of a goat manure–food waste mixture incorporated with seaweed (*G. funicularis*) biochar.

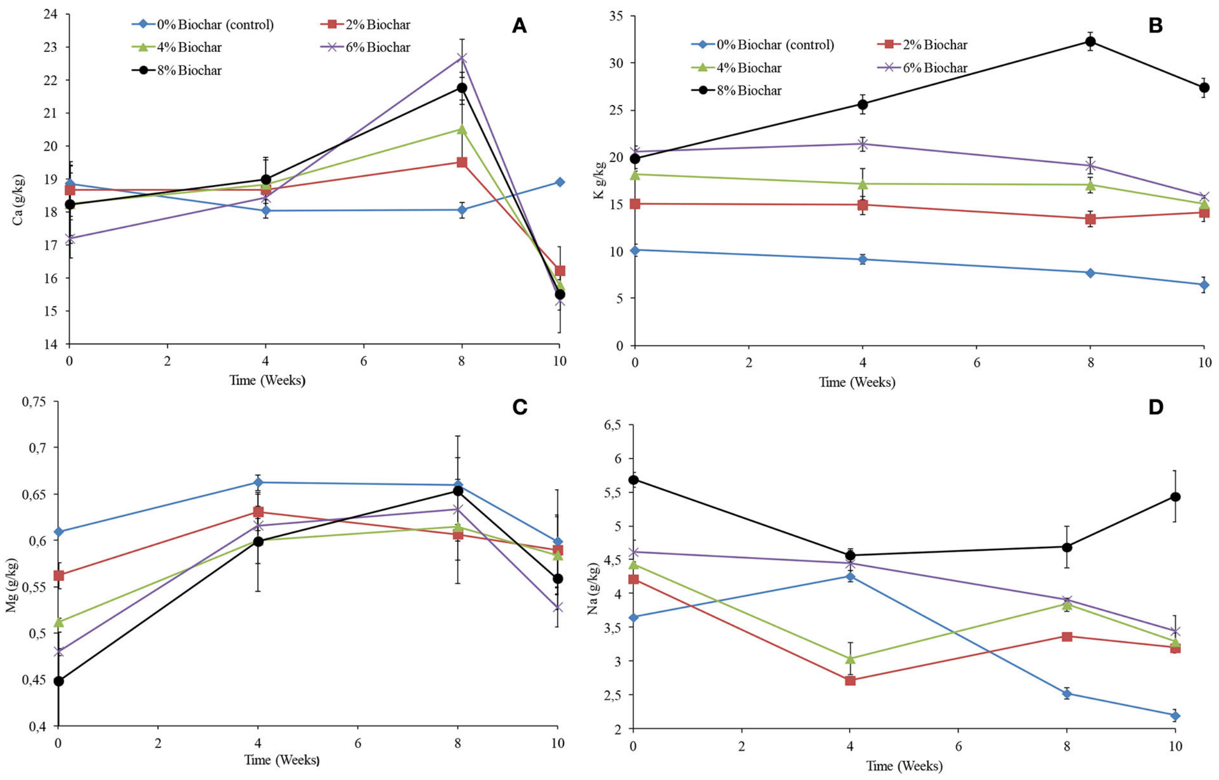


FIGURE 6
Changes in extractable **(A)** (Ca), **(B)** (K), **(C)** (Mg), and **(D)** (Na) after 10 weeks of vermicomposting of a goat manure–food waste mixture amended with seaweed (*G. funicularis*) biochar. Error bars indicate standard deviation.

crops. However, it will be interesting to observe the changes in soil EC after the moderate amendment of sandy soils, which leach faster with these vermicomposts. In a review, Gondek et al. (2020) highlighted that other studies have used composts with conductivities higher than 4 mS/m with no crop phytotoxicity in the second and third seasons. It is recommended to fully evaluate such vermicomposts on their agronomic effectiveness, especially with saline-tolerant crops such as wheat and barley. Also, such vermicomposts have been observed to be more ideal for growing plants rather than for seedling emergency and growth.

The incorporation of biochar did not influence the trend of change in a C/N ratio as all treatments followed the same trend. The C/N ratio is the key indicator of biodegradation during the vermicomposting process (Karwal and Kaushik, 2021), and C/N of <20 has been reported to represent mature vermicompost through a C/N ratio of below 15 representing a much more stable compost (Bernal et al., 2009). In our study, it was observed that the treatments that had biochar incorporated at 6–8% resulted in much more stable vermicompost though even the control resulted in mature vermicompost with a C/N ratio of below 20. The decrease in the C/N ratio may be due to the accumulation of nitrogenous compounds, the release of CO_2 by earthworm metabolism, and enzyme–microbe-induced decomposition of organic matter (Bhat et al., 2015; Karwal and Kaushik, 2021). This was also observed in a study by Ravindran and Mnkeni (2016) who reported that the C/N ratio decreases may be due to a higher loss of carbon accompanied by an increase in nitrogen during vermicomposting of waste paper and chicken manure. In the study, the decrease in C/N may have been a result of the rapid breakdown of organic matter for microbial metabolism. When you incorporate biochar into vermicompost, you may get faster maturity relative to the control without biochar. The inclusion of biochar does not result in reduced decomposition but rather enhanced decomposition as observed in the study.

The humification parameters showed a different trend with the control having the highest humification parameters though they were not significantly different from the other treatments. As observed in our study, the incorporation of biochar does not result in reduced humification parameters. Mature compost has been indicated to have a humification ratio of >7, which was achieved in all treatments in our study (Bernal et al., 2009). However, according to Bernal et al. (2009) the humification index, polymerization index, and percentage of humic acids were all below the recommended levels for mature compost. This may be because the humification takes place after the initial decomposition during vermicomposting; therefore, it might be interesting to do this vermicomposting over a longer period to see whether humification can be improved. It is interesting that the C/N ratio indicated mature vermicompost unlike the humification parameters. There is still a need to evaluate other parameters other than humification parameters that are critical in the evaluation of compost maturity (Li et al., 2015).

Influence of seaweed biochar incorporation on nutrient transformations

An incorporation rate of biochar of between 6 and 8% resulted in the highest Olsen extractable P after 10 weeks of vermicomposting. The peak concentration of Olsen P was observed between weeks 6 and 8, which unfortunately was when the vermicompost was not yet matured. The decline in Olsen P may be due to the leaching of the nutrients in the leachate. The higher the biochar, the higher the concentrations of Olsen P observed. The higher concentrations in vermicomposts may be due to various earthworm activities during vermicomposting with the enzymes that help the release of phosphorus from feedstock (Sharma and Garg, 2019). According to the Food and Agriculture Organization of the United Nations, the potassium content in organic fertilizer should not be <1.5%, whilst the concentration of calcium and other essential micronutrients should be in the range from 0.01 to 0.05%. In this study, the concentration of potassium was above 1.5%, which means the incorporation of biochar may enhance the concentration of potassium in composts. Zhang et al. (2016) found that the concentration of Na ions was lower in the composted mixture amended with biochar as compared to the mixture without biochar addition. However, in this study that was not the case, and this might be attributed to the origin of the material that was used to prepare the biochar, which is from the marine environment where salinity is higher. It will be important to monitor the changes in soil physical properties when this seaweed biochar amended vermicompost is used as the soil amendment. The increase in exchangeable calcium and magnesium is ascribed to the higher content of these nutrients in the materials used. In the study, that was not the case, the increase in calcium and magnesium could be attributed to the effect of organic acids produced during the process of decomposition, which enhances the solubility of calcium and magnesium. The incorporation level of biochar increased the potassium concentration, and this may be due to the biochar used which had high amounts of potassium from the first experiment.

Conclusion

The study observed that biochar incorporation does not really influence the biodegradation process. However, higher inclusion levels of the seaweed biochar in vermicomposts might result in elevated EC. In terms of nutrients, the seaweed biochar resulted in significantly higher Olsen extractable P levels as compared to the control. An optimized level of 6% to 8 biochar incorporation ratio can be recommended in terms of nutrition and decomposition during vermicomposting of food waste–goat manure mixture. During vermicomposting, the peak concentration of elements such as P was observed before the vermicompost indicated maturity based on the C/N ratio and humification parameter. The vermicompost in this study could be ideal for growing, mainly saline-sensitive crops such as wheat, barley, and other grasses, not for seedling growth. It will be interesting to evaluate the changes in soil parameters and plant growth when vermicompost with seaweed biochar incorporated between 6 and 8% is used.

Statement of novelty

Enhanced vermicomposting process makes use of marine biomass biochar to enhance nutrient composition whilst other researchers used terrestrial biomass. It creates a enhanced frontier in marine biomass valorization.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

Material preparation, data collection, and analysis were performed by AK, HM, BH, and WG. The first draft of the manuscript was written by AK. All authors commented on previous versions of the manuscript. All authors contributed to the study conception and design. All authors read and approved the final manuscript.

Funding

This study was funded by research funds from the University of Namibia through an MSc study bursary to AK.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Agri Laboratory Association of Southern Africa (AgriLASA) (2004). *Soil Handbook*. Pretoria: Agri Laboratory Association of Southern Africa.

Bernal, M. P., Alburquerque, J., and Moral, R. (2009). Composting of animal manures and biodiversity. *Biodiver. Conserv.* 7, 419–433. doi: 10.1016/j.biortech.2008.11.027

Bhat, S. A., Singh, J., and Vig, A. P. (2015). Potential utilization of bagasse as feed material for earthworm Eisenia fetida and production of vermicompost. *SpringerPlus* 4, 11. doi: 10.1186/s40064-014-0780-y

Chen, X., Zhao, Y., Zhang, C., Zhang, D., Yao, C., Meng, Q., et al. (2020). Speciation, toxicity mechanism and remediation ways of heavy metals during composting: a novel theoretical microbial remediation method is proposed. *J. Environ. Manag.* 272, 111109. doi: 10.1016/j.jenvman.2020.111109

Gondek, M., Weindorf, D. C., Thiel, C., and Kleinheinz, G. (2020). Soluble salts in compost and their effects on soil and plants: a review. *Compost Sci. Utiliz.* 28, 2, 59–75. doi: 10.1080/1065657X.2020.1772906

Hu, X., Huang, X., Zhao, H., Liu, F., Wang, L.u., Xin, Z., et al. (2021). Possibility of using modified fly ash and organic fertilizers for remediation of heavy-metal-contaminated soils. *J. Clean. Prod.* 284:124713. doi: 10.1016/j.jclepro.2020.124713

Jain, M. S., Rohit, J., and Ajay, S. K. (2018). Biochar amendment for batch composting of nitrogen rich organic waste: effect on degradation kinetics, composting physics and nutritional chemical criteria for compost maturity assessment. *A review. Bioresour. Technol.* 22, 5444–5453. doi: 10.1016/j.biortech.2018.01.038

Karwal, M., and Kaushik, A. (2021). Bioconversion of lawn waste amended with kitchen waste and buffalo dung in to value –added vermicompost using Eisenia foetida to alleviate landfill burden. *J. Mater Cycles Waste Manag.* 23, 358–370. doi: 10.1007/s10163-020-01101-7

Katakula, A. A. N., Gawanab, W., Itanna, F., and Mupambwa, H. A. (2020). The potential fertilizer value of Namibian beach-cast seaweed (*Laminaria pallida* and *Gracilariopsis funicularis*) biochar as a nutrient source in organic agriculture. *Sci. Afr.* 10, e00592. doi: 10.1016/j.sciaf.2020.e00592

Katakula, A. A. N., Handura, B., Gawanab, W., Itanna, F., and Mupambwa, H. A. (2021). Optimized vermicomposting of a goat manure-vegetable food waste mixture for enhanced nutrient release. *Scient. Afr.* 12, e00727. doi: 10.1016/j.sciaf.2021.e00727

Khan, M. B., Xiaoqiang, C., Ghulam, J., Ugit, L., Afsheen, Z., Yasir, H., et al. (2019). Eisenia fetida and biochar synergistically alleviate the heavy metals content during valorization of biosolids via enhancing vermicompost quality. *Sci. Total Environ.* 684, 597–609. doi: 10.1016/j.scitotenv.2019.05.370

Kizito, S., Luo, H., Lu, J., Bah, H., Dong, R., and Wu, S. (2019). Role of nutrient-enriched biochar as a soil amendment during maize growth: Exploring practical alternatives to recycle agricultural residuals and to reduce chemical fertilizer demand. *Sustainability* 11, 3211. doi: 10.3390/su11113211

Kuo, S. (1996). "Phosphorus," in *Methods of Soil Analysis. Part 3 Chemical Methods*, eds D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, et al. (Madison: Soil Science Society of America), Book Series No. 5, 869–912.

Li, Z., Huang, G., Yu, H., Yang, Z., and Huang, W. (2015). Critical factors and their effects on product maturity in food waste Composting. *Environ. Monit. Assess.* 187:217. doi: 10.1007/s10661-015-4430-9

Lukashe, S. N., Mupambwa, H. A., Green, E., and Mnkeni, P. N. S. (2019). Inoculation of fly ash amended vermicompost with phosphate solubilizing bacteria (*Pseudomonas fluorescens*) and its influence on vermi-degradation, nutrient release and biological activity. *Waste Manag.* 83, 14–22. doi: 10.1016/j.wasman.2018.10.038

Makini, G. V., Ndukhu, H. O., Muraya, M., and Kirimi, I. M. (2020). Effects of goat manure-based vermicompost on soil chemical properties under garlic production in meru south and manyatta sub-counties. *Int. J. Eng. Appl. Sci. Technol.* 4, 91–99. doi: 10.33564/IJEAST.2020.v04i09.009

Mupambwa, H. A., Haulofu, M., Nciizah, A. D., and Mnkeni, P. N. S. (2022). "Vermicomposting technology: a sustainable option for waste beneficiation," in *Handbook of Waste Biorefinery*, eds E. Jacob-Lopes, L. Queiroz Zepka, and M. Costa Deprá (Cham: Springer). doi: 10.1007/978-3-031-06562-0_21

Mupambwa, H. A., and Mnkeni, P. N. S. (2016). Eisenia fetida stocking density optimization for enhanced bioconversion of fly ash enriched vermicompost. *J. Environ. Qual.* 45, 1087–1095. doi: 10.2134/jeq2015.07.0357

Ravindran, B., and Mnkeni, P. N. S. (2016). Bio-optimization of the carbon-to-nitrogen ratio for efficient vermicomposting of chicken manure and waste paper using *Eisenia fetida*. *Environ. Sci. Pollut. Resour*. 23, 16965–16976. doi: 10.1007/s11356-016-6873-0

Sanchez-Monedero, M. A., Roig, A., Martinez-Pardo, C., Cegarra, J., and Paredes, C. (1996). A microanalysis method for determining total organic carbon in extracts of humic substances: Relationships between total organic carbon and oxidisable carbon. *Bioresour. Technol.* 57, 291–295. doi: 10.1016/S0960-8524(96)00078-8

Schoenau, J. J., and O'Halloran, I. P. (2006). "Sodium bicarbonate-extractable phosphorus," in *Soil Sampling and Methods of Analysis, 2nd Edn*., ed M. R. Carter (Boca Raton, FL: Canadian Society of Soil Science, Canada), 89–95. doi: 10.1201/9781420005271.ch8

Sharma, K., and Garg, V. K. (2019). Recycling of lignocellulosic waste as vermicompost using earthworm Eisenia fetida. *Environ. Sci. Pollut. Res. Int*. 26, 14024–14035. doi: 10.1007/s11356-019-04639-8

Simms, T., Chen, H., and Mahato, G. (2020). Dope-depended effect of biochar as soil amendment on reducing copper phytotoxicty and mobility. *Int. J. Environ. Resour*. 14, 751–759. doi: 10.1007/s41742-020-00293-y

Wang, H., Tianbao, R., Yuqing, F., Kouzhu, L., Huilin, F., Guoshun, L., et al. (2020). Effects of the application of biochar in four typical agricultural soils in China. *Agronomy* 10, 351. doi: 10.3390/agronomy10030351

Were, S. A., Rama, D. N., Janice, E. T., Eunice, W. M., James, W., Muthomi, L. M., et al. (2019). Effect of vermicompost and biochars from different crop residues in management of root rot of common bean (*Phaseolus vulgaris L.*). *Int. J. Res. Agric. Sci.* 6, 2348–3997.

Zhang, J., Chen, G., Sun, H., Zhou, S., and Zou, G. (2016). Straw biochar hastens organic matter degradation and produces nutrient-rich compost. *Bioresour. Technol.* 200, 876–883. doi: 10.1016/j.biortech.2015.11.016

Zheng, G., Xiankai, W., Tongbin, C., Jun, Y., Junxing, Y., Junwan, L., et al. (2020). Passivation of lead and cadmium and increase of the nutrient content during sewage sludge composting by phosphate amendments. *Environ. Res.* 185, 109431. doi: 10.1016/j.envres.2020.109431

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 20 December 2022
DOI 10.3389/fsufs.2022.1077363

Check for updates

OPEN ACCESS

EDITED BY
Claudio Bellia,
University of Catania, Italy

REVIEWED BY
Mariarita Cammarata,
University of Catania, Italy
Mario Chizzotti,
Universidade Federal de Viçosa, Brazil
Mürsel Özdoğan,
Aydin Adnan Menderes
University, Turkey

*CORRESPONDENCE
Vincenzo Lopreiato
vincenzo.lopreiato@unime.it

SPECIALTY SECTION
This article was submitted to
Waste Management in
Agroecosystems,
a section of the journal
Frontiers in Sustainable Food Systems

RECEIVED 22 October 2022
ACCEPTED 28 November 2022
PUBLISHED 20 December 2022

CITATION
Bionda A, Lopreiato V, Crepaldi P, Chiofalo V, Fazio E, Oteri M, Amato A and Liotta L (2022) Diet supplemented with olive cake as a model of circular economy: Metabolic and endocrine responses of beef cattle.
Front. Sustain. Food Syst. 6:1077363.
doi: 10.3389/fsufs.2022.1077363

Diet supplemented with olive cake as a model of circular economy: Metabolic and endocrine responses of beef cattle

Arianna Bionda[1], Vincenzo Lopreiato[2]*, Paola Crepaldi[1], Vincenzo Chiofalo[2,3], Esterina Fazio[2], Marianna Oteri[2], Annalisa Amato[2] and Luigi Liotta[2]

[1]Department of Agricultural and Environmental Sciences, Production, Landscape and Energy, University of Milan, Milan, Italy, [2]Department of Veterinary Sciences, University of Messina, Messina, Italy, [3]Consortium of Research for Meat Chain and Agrifood (CoRFilCarni), Messina, Italy

Introduction: Integrating by-products into livestock diet represents a great opportunity for implementing the concept of circular economy while reducing feed costs. Olive cake (OC) is considered an agro-industrial waste, but the high content of valuable metabolites makes it a promising feed integration. Therefore, this study investigated the effect of OC integration in beef cattle diet on different blood parameters.

Methods: Forty-eight young growing fattening Limousines-—24 bulls (body weight 350 ± 15 kg) and 24 heifers (280 ± 10 kg)—, aged 240 ± 20 days, were randomly allocated to 1 of 3 dietary treatments: concentrate at 0% (Control group: CTR), 10% (Low-olive cake group: L-OC), or 15% (High-olive cake group: H-OC) of OC inclusion. Blood samples and body weights were collected before administrating the supplemented diet (0 d), at the end of the stocker growing phase (56 d), and at the end of the fattening (147 d). After being slaughtered, animal carcasses were weighted. A linear regression model was fitted for each blood parameter with the 0 d as covariate and diet, time, sex, diet × time, and diet × sex as fixed effects.

Results: In males, body weight was highest in CTR, but carcass weight was similar in all the groups. All the blood parameters were within physiological ranges, independently from the animal diet. CTR group showed the highest alanine aminotransferase (ALT, $P = 0.0027$) and creatine kinase ($P = 0.0119$), whereas total bilirubin ($P = 0.0023$) was higher in H-OC than in CTR. Moreover, ALT was highest in CTR at 56 d, becoming similar in all the groups at 147 d ($P = 0.0280$). Instead, the increase observed in total cholesterol from 56 to 147 d was lower in H-OC compared with CTR and L-OC ($P = 0.0451$). A significant effect of diet × sex interaction was observed on triglycerides, urea, liver enzymes, and insulin. These data support the OC inclusion of up to 15% of the concentrate with no detrimental effect on beef cattle metabolic status.

Discussion: In conclusion, OC can be considered as a component in beef diet giving an opportunity to improve agriculture sustainability.

KEYWORDS

beef cattle, olive cake, metabolism, circular economy, olive by-products

1. Introduction

In the Mediterranean area, the production of olive oil is significant; indeed, it contributes to 76% of the total production of olive oil, with Spain, Italy, and Greece being the main producers (Berbel and Posadillo, 2018). It is estimated that in European countries about 11.8 million tons of biomass are produced from the olive tree pruning process (Berbel and Posadillo, 2018) and since the production of olive oil is an important source of energy and water consumption, the increase in the olive oil industry has led to an inevitable rising of environmental impact. Besides the considerable emissions, it generates a relevant amount of waste that must be disposed (Salomone and Ioppolo, 2012). The main by-products generated from olive oil process are olive mill wastewater and olive cake (Foti et al., 2022). However, because of its properties, processing waste like olive cake (OC) could be used in different sectors, such as energy generation, food products, pharmaceutical industry, and animal feed (Espeso et al., 2021). In particular, the use of olive cake as animal feed is an interesting and sustainable alternative to its disposal, because it may decrease the costs associated with animal feeding, valorizing a waste biomass and at the same time improving the quality of the products (Keleş, 2015; Castellani et al., 2017; Vastolo et al., 2019). In fact, the spread of its use as integrator in animal feeding is mainly related to the presence of substances with antioxidant and radical scavenging activity, and to its richness in monounsaturated fatty acids (MUFAs) (Ghanbari et al., 2012). There are many studies on the incorporation of this by-product in livestock diet, for example in broilers (Al-Harthi, 2016), pigs (Joven et al., 2014; Liotta et al., 2019), goats (Alkhtib et al., 2021; El Otmani et al., 2021), sheep Chiofalo et al., 2004; Vargas-Bello-Pérez et al., 2013, dairy cattle (Zilio et al., 2015; Chiofalo B. et al., 2020; Neofytou et al., 2020), and beef cattle (Estaún et al., 2014; Branciari et al., 2015; Chiofalo V. et al., 2020).

According to Estaún et al. (2014), the addition of pitted and dehydrated olive cake at rate of 10 or 20% in the concentrate led to no differences in terms of either animal performance for the whole growth period or rumen fermentation parameters in Frisian steers from 100 to 450 kg of body weight. In addition, lack of differences found at rumen fermentation level (pH and volatile fatty acids) suggests that olive cake supplementation (10 or 20% in the concentrate) does not negatively affect the activity of microbial populations, at least in Frisian steers. From these outcomes it is reasonable to suppose that including pitted and dehydrated olive cake in the diet of beef cattle should not affect animal performance and at the same time might be suitable to implement a supply chain system at the economic and sustainable level.

However, to the best of our knowledge, a few studies have been carried out to investigate the effect of olive cake on the metabolic and endocrine traits of beef cattle. Hence, the aim of this study was to determine if the changes in plasma triglycerides (TG), total cholesterol (TCHOL), glucose (GLU), total bilirubin (TBIL), aspartate aminotransferase (AST), alanine aminotransferase (ALT), creatine kinase (CK), lactate dehydrogenase (LDH), and urea in heifers and bulls are substantial enough to indicate the need to establish specific reference intervals also for young growing fattening Limousine bulls and heifers. The direction and magnitude of the changes in these parameters could be used as diagnostic tools for the detection and monitoring of metabolic and endocrine traits that could arise during growth in this species fed concentrate with different percentages of olive cake inclusion.

Abbreviations: OC, olive cake; FA, fatty acids; TG, triglycerides; TCHOL, total cholesterol; GLU, glucose; TBIL, total bilirubin; ASP, aspartate aminotransferase; ALT, alanine aminotransferase; CK, creatine kinase; BW, body weight; CTR, control group (0% inclusion); L-OC, low-olive cake group (10% inclusion); H-OC, high-olive cake group (15% inclusion); ADG, average daily gain; CW, carcass weight; LSM, least square mean.

2. Materials and methods

The experimental protocol was approved by the Ethical Committee of the Department of Veterinary Science, University of Messina, Italy (code 041/2020). The research complied with guidelines of Good Clinical Practices (The European Agency for the Evaluation of Medicinal Products, 2000) and the Italian and European regulations on animal welfare (Directive 2010/63/EU) (Council of the European Union, 2010).

2.1. Animal management and experimental design

The experiment was carried out using a total of 48 Limousine young growing fattening animals (24 bulls and 24 heifers), aged 250 ± 20 days at the time of the first sampling. The initial body weight (BW) was on average 350 ± 15 kg for bulls and 280 ± 10 kg for heifers. This breed was chosen because it is the most diffused in Sicily for breed production. All animals were housed in the same pen of a semi-open straw-bedded barn located in Santa Croce Camerina (Ragusa, Italy, 36°49′38″N 14°31′26″E). The farm is located within the Hyblean Mediterranean area with an unequally distributed rainfall throughout the year. Annual mean rainfall is about 700 mm. The annual average temperature is 19.58°C (with an average of maximum and minimum temperature of 21 and 17°C, respectively).

Animals were raised according to an approved UE disciplinary called "QS Sicilia," which allows the inclusion of olive cake in feed for beef cattle not <10% of the diet, as a strategy for the recovery of agro-industrial by-products.

After a 2-week adaptation period, animals were randomly allocated to one of three dietary treatments according to their BW: inclusion of olive cake at 0% (Control group: CTR), 10% (Low-olive cake group: L-OC), or 15% (High-olive cake group: H-OC) in the concentrate. The compositions of the concentrates and of the OC used for the study are reported in Table 1. All the animals were allowed *ad libitum* access to straw and water. After adaptation, animals received their concentrate (equal to 2% of their body weight, on average) twice daily (7.00 a.m. and 3.00 p.m.). During the whole experimental period (147 days), none of the animals had health problems. When animals reached the endpoint, they were transported to a licensed slaughterhouse located 20 min (19.2 km) away from the farm. Animals fasted for 12 h before slaughter, which was performed according to EU Regulations. The interval between the first and the last slaughter was 18 days.

TABLE 1 Feed and nutrient composition of concentrate with 0% (Control group: CTR), 10% (Low-olive cake group: L-OC), or 15% (High-olive cake group: H-OC) of olive cake (OC) inclusion fed to growing fattening Limousine bulls and heifers.

	CTR	L-OC	H-OC
Feed composition (% DM)			
Corn flour	34.00	35.00	35.00
Soybean meal 44	18.00	15.00	15.00
Corn flakes	13.00	13.00	13.50
Destoned olive cake	–	10.00	15.00
Wheat bran	11.00	4.00	4.00
Barley	10.00	9.00	8.00
Sunflower	7.00	5.00	1.40
Vitamin and mineral mix*	4.00	4.00	3.30
Soybean flakes	2.00	4.00	4.00
Carob	1.00	1.00	0.80
Saccharomyces cerevisiae, live yeast	0.40	0.40	0.40
Sodium bicarbonate	0.80	0.80	0.50
Sodium chloride	0.50	0.50	0.50
Sodium propionate	0.30	0.30	0.40
Calcium carbonate	0.30	0.30	0.30
Dicalcium phosphate	0.20	0.20	0.20
Nutrient composition			
Dry matter	89.20	88.50	89.00
Crude protein (% DM)	18.50	18.20	18.30
Crude fat (% DM)	5.00	5.40	6.10
Ash (% DM)	5.00	5.10	4.90
Acid detergent fiber (% DM)	8.50	10.60	11.50
Neutral detergent fiber (% DM)	44.30	46.70	45.30
Starch (% DM)	44.00	43.90	43.40
Net energy (UFV/kg of DM)**	1.09	1.08	1.08

*Vitamin E (1,500 UI/head/d), Selenium (0.30 ppm/head/d), Zinc (1,000 ppm/head/d).
**The UFV/kg of dry matter intake of concentrate is the value of energy density according to the INRA feeding system, corresponding to the Net energy for meat production (in kcal/kg)/1,760.

2.2. Animal measurements in vita and post-mortem

Animals of each pen, before feed distribution, were individually weighed at the beginning of the trial, after 56 days, and at the end of the trial (147 days) using Brecknell PS-2000 Veterinary Floor Scale (capacity: 1,000 kg, readability: 0.5 kg). Individual average daily gain (ADG) was also calculated. At the end of the trial, animals were slaughtered, and after slaughter the hot carcass weight (CW) was recorded, and the dressing percentage was calculated. pH was determined 1 and 24 h after slaughter using a portable pH meter (Hanna Instruments, Woonsocket, RI, USA) and combined glass electrode, inserted ∼5 cm into the *longissimus thoracis* muscle.

2.3. Blood samples collection and analysis

The blood samples were collected at the beginning (day 0, before administrating treated concentrates) and on days 56 and 147 of the trial, in the morning before dispensing the concentrate. Blood was collected from the tail vein by trained veterinarians through venipuncture into 10-mL tubes containing clot activator and separating gel (Terumo Corporation, Tokyo, Japan). Blood samples were centrifuged for 10 min at 2,000 × g; the supernatant serum was collected and stored at −20°C until analyses.

Biochemical lipids (TG, TCHO), liver (TBIL, AST, ALT, LDH), renal (Urea), and muscular (CK), parameters were analyzed by enzymatic colorimetric method, using an automated spectrophotometry (Biotechnical Instrument BP 3500) and reagents of the same commercial house.

Glucose concentration was measured by automated spectrophotometry (Biotecnica Instruments BT 3500) using the colorimetric enzymatic method GOD-POD.

Insulin concentration was analyzed using the Immulite® two-site chemiluminescent immunometric assay (Maglium 800), with a sensitivity of 0.5 µIU/mL and intra- and inter-assay coefficients of variation equal to 1.56 and 4.07% at insulin concentrations of 16.54 and 45.804 µIU/mL.

2.4. Statistical analysis

Statistical analyses were performed with JMP®, Version 16 (SAS Institute Inc., Cary, NC). Appropriate descriptive statistics

TABLE 2 Means and results of the model for all the measured performance traits: body weight (BW), average daily gain (ADG), carcass weight (CW), dressing, and pH.

	Bulls			Heifers			SEM*	Diet	Sex	Diet x Sex
	CTR	L-OC	H-OC	CTR	L-OC	H-OC				
BW (kg)	630.51	549.46	553.23	467.32	481.75	486.30	15.64	0.0794	**<0.0001**	**0.0042**
ADG (kg/d)	1.62	1.42	1.41	1.00	1.25	1.06	0.08	0.3829	**<0.0001**	**0.0276**
CW (kg)	358.12	333.52	344.98	277.07	267.63	286.68	10.76	0.2477	**<0.0001**	0.5657
Dressing (%)	56.86	60.62	62.23	59.28	55.84	58.95	1.01	**0.0308**	**0.0312**	**0.0028**
pH at 1 h	6.66	6.48	6.37	6.40	6.33	6.43	0.08	0.2199	0.0829	0.1629
pH at 24 h	5.66	5.81	5.82	5.78	5.70	5.76	0.05	0.1341	0.5652	**0.0096**

Factors' significant P-values (< 0.05) are reported in bold.
*Greatest standard error of the mean.

was generated for all the variables. The correlation between all the parameters was expressed using Pearson's coefficient (r).

The blood parameters of interest (Y) were modelized as follows:

$$Y_{ijk} = m + D + T + S + DT + DS + T0 + e$$

Where m is the mean, D is the diet (CTR, L-OC, or H-OC), T is the time of sampling (day 56 or day 147 of the trial), S is the sex of the animal (male or female), DT is the interaction between the diet and the time of sampling, DS is the interaction between the diet and the sex, $T0$ is the covariate representing the parameter level at the beginning of the trial (before administering the supplemented concentrated), and e is the random residual. With regard to the performance parameters, only the diet (D), the sex (S), and their interaction (DS) were included as factors. A logarithmic transformation was applied when necessary. When factors or interactions resulted significant, the Tukey-Kramer *post-hoc* test was used to identify the significantly different levels.

Differences were considered to be statistically significant when $P < 0.05$.

3. Results

Results of animal performance are reported in Table 2. As expected, differences between heifers and bulls were observed for all the variables with the exception of pH. Even though the diet was significant for dressing ($P = 0.0308$, with higher values for H-OC than CTR), when we considered heifers only, we observed similar values for all the performance-related variables. Instead, within bulls, we observed that the body weight was higher in the CTR group, but this was not supported by the average daily gain and the carcass weight, which were similar in all the diet groups. Consequently, the dressing resulted higher in H-OC than CTR bulls, with intermediate values for L-OC ones. One factor possibly affecting BW and CW is dry matter intake; several studies on ruminants showed no difference in feed intake between traditional and OC-integrated diets (Yáñez Ruiz et al., 2004; Awawdeh and Obeidat, 2013; Mele et al., 2014; de Evan et al., 2020) but we cannot exclude it, since it was not assessed in the present study, it being carried out in a commercial farm. It is possible that this result might also have been influenced by a difference in the feed intake among the groups; however, it was not possible to assess this data because the trial was performed in a commercial farm.

In this study, a wide range of blood plasma biomarkers associated with the metabolic variation was chosen. The descriptive statistics of the blood metabolic biomarker concentrations by sex, physiological stage, and diet, as well as the P-values and R^2 resulted from the model applied to each blood analyte are reported in Table 3. The parameters significantly affected by the diet, the diet × time interaction (indicating a different effect of the diet according to the time of sampling), and the diet × sex interaction (indicating a different effect of the diet on heifers than on bulls) are plotted in Figures 1–3, respectively.

Data obtained showed that AST, TBIL, urea, TCHO, TG and insulin significantly increased from 56 to 147 d, whereas ALT and GLU decreased ($P < 0.05$).

CTR group showed the highest ALT ($P = 0.0027$) and CK ($P = 0.0119$), whereas TBIL ($P = 0.0023$) was higher in H-OC than in CTR group (Figure 1). Moreover, ALT was higher in CTR at 56 d ($P = 0.0280$), but it was similar in all the groups at 147 d ($P = 0.028$ for diet × time interaction, Figure 2B). Instead, the increase in the level of TCHO observed from 56 to 147 d was lower in H-OC compared with both CTR and L-OC groups ($P = 0.0451$ for diet x time interaction, Figure 2A). Compared with bulls, heifers showed higher TCHO ($P = 0.0131$), TG ($P < 0.0001$), and GLU ($P = 0.0002$) and lower insulin ($P = 0.0075$) concentrations.

The diet × sex interaction was significant for AST ($P = 0.0005$), ALT ($P = 0.0015$), LDH ($P = 0.0102$), and urea

TABLE 3 Mean and standard deviation of all the blood analyte measurements, and *P*-values (in bold when significant) and R^2 of the applied model.

Sex	**Heifers**						**Bulls**												
Time of sampling	**Day 56**			**Day 147**			**Day 56**			**Day 147**			**P-values**						
Diet	**CTR**	**L-OC**	**H-OC**	**CTR**	**L-OC**	**H-OC**	**CTR**	**L-OC**	**H-OC**	**CTR**	**L-OC**	**H-OC**	**Diet**	**Time**	**Sex**	**Diet × Time**	**Diet × Sex**	**T0**	R^2
AST (UI/l)	82.88 ± 13.77	122.00 ± 46.00	105.63 ± 21.51	96.38 ± 49.53	153.25 ± 93.32	92.75 ± 18.89	79.63 ± 15.80	83.75 ± 14.80	92.63 ± 22.49	122.88 ± 82.07	101.25 ± 26.38	147.75 ± 45.03	0.6284	**0.0071**	0.9583	0.9613	**0.0005**	0.0096	0.27
ALT (UI/l)	34.38 ± 7.82	31.75 ± 4.23	32.13 ± 4.29	26.50 ± 4.72	35.25 ± 8.92	26.75 ± 4.92	28.50 ± 11.51	29.38 ± 8.11	28.75 ± 3.45	22.13 ± 6.98	25.63 ± 6.32	29.88 ± 4.64	**0.0027**	**0.0048**	0.7078	**0.028**	**0.0015**	**<0.0001**	0.53
LDH (UI/l)	2,987.00 ± 362.33	3,102.50 ± 362.05	3,347.50 ± 400.66	2,588.38 ± 788.48	3,430.38 ± 1,031.14	2,823.63 ± 835.99	2,888.25 ± 463.15	3,024.50 ± 389.81	3,010.25 ± 445.75	3,022.63 ± 408.94	2,987.25 ± 378.14	3,589.88 ± 632.96	0.4343	0.9063	0.1878	0.62	**0.0102**	**0.0006**	0.21
CK (UI/l)	328.75 ± 129.95	224.63 ± 75.93	333.00 ± 175.50	279.43 ± 110.34	311.50 ± 197.26	200.25 ± 65.66	328.75 ± 84.85	191.13 ± 53.34	321.13 ± 187.75	276.25 ± 71.92	243.88 ± 174.92	265.25 ± 214.03	**0.0119**	0.1988	0.6779	0.0696	0.4939	0.3498	0.16
Total bilirubin (mg/dl)	0.14 ± 0.03	0.16 ± 0.04	0.19 ± 0.03	0.23 ± 0.05	0.26 ± 0.05	0.24 ± 0.05	0.13 ± 0.01	0.16 ± 0.02	0.17 ± 0.02	0.22 ± 0.05	0.23 ± 0.05	0.25 ± 0.03	**0.0023**	**<0.0001**	0.139	0.1558	0.9434	0.5509	0.59
Urea (mg/dl)	15.00 ± 1.69	18.25 ± 2.05	14.38 ± 1.85	27.75 ± 36.92	18.38 ± 2.33	15.50 ± 2.73	14.88 ± 2.10	13.00 ± 1.93	14.00 ± 2.14	14.63 ± 2.67	15.38 ± 2.26	16.63 ± 2.07	0.0797	**0.033**	0.118	0.1493	**<0.0001**	0.1462	0.36
Total Cholesterol (mg/dl)	109.50 ± 22.51	93.88 ± 11.10	106.00 ± 18.15	158.25 ± 34.43	136.38 ± 36.54	98.13 ± 31.45	95.75 ± 10.94	92.50 ± 22.17	91.50 ± 20.62	116.13 ± 32.43	119.88 ± 29.40	119.25 ± 16.39	0.3035	**<0.0001**	**0.0131**	**0.0451**	0.1754	**<0.0001**	0.51
Triglycerides (mg/dl)	26.63 ± 6.28	27.88 ± 2.90	26.75 ± 4.71	27.38 ± 4.37	33.75 ± 4.83	23.50 ± 5.98	19.75 ± 3.20	19.50 ± 2.93	22.25 ± 4.56	23.38 ± 4.24	25.88 ± 2.95	26.50 ± 7.21	0.7072	**0.003**	**<0.0001**	0.0548	**0.0061**	0.0506	0.41
Glucose (mg/dl)	76.13 ± 8.43	78.75 ± 13.02	85.13 ± 15.99	66.75 ± 11.30	58.88 ± 12.54	76.13 ± 15.68	64.63 ± 9.07	63.25 ± 7.52	68.50 ± 6.65	52.63 ± 25.72	52.88 ± 6.20	61.00 ± 10.11	0.1915	**<0.0001**	**0.0002**	0.4932	0.3517	**<0.0001**	0.5
Insulin (mUI/ml)	1.11 ± 0.72	1.16 ± 0.34	0.91 ± 0.14	1.30 ± 0.73	1.87 ± 0.52	1.20 ± 0.43	0.76 ± 0.07	0.83 ± 0.24	1.09 ± 0.50	2.27 ± 0.28	1.73 ± 0.47	2.29 ± 0.34	0.418	**<0.0001**	**0.0075**	0.8163	**0.0007**	**0.0053**	0.5

CTR, control group, olive cake inclusion; L-OC, low olive cake group, 10% inclusion; H-OC, high-olive cake group, 15% inclusion.

10.3389/fsufs.2022.1077363

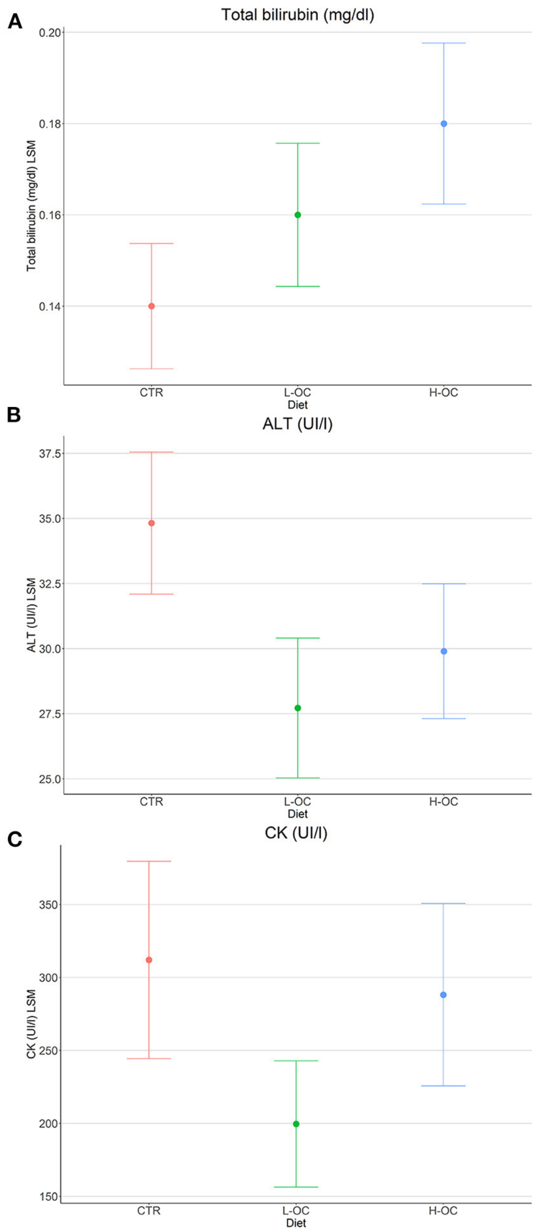


FIGURE 1
Significant effect of the diet on total bilirubin **(A)**, ALT **(B)**, and creatin kinase [CK, **(C)**]. The parameters' least square mean (LSM) and standard error are represented for all the groups with different olive cake inclusions, namely control (CTR, 0%), Low-olive cake (L-OC, 10%), and High-olive cake (H-OC, 15%) groups.

($P < 0.0001$) (Figures 3B–E). Specifically, their concentrations were similar in heifers and bulls of CTR and H-OC groups, but higher in heifers than bulls of L-OC group. Considering bulls only, ALT was higher in CTR than L-OC group (Figure 3C), whereas LDH and TG ($P = 0.0061$) were higher in H-OC than L-OC group (Figures 3A, E); instead, no differences among the three diets were observed in heifers. On the other and, in heifers, urea was higher in L-OC than H-OC (Figure 3B), whereas bulls showed similar values independently from the diet. Insulin ($P = 0.0007$) was higher in bulls than in heifers of CTR and H-OC groups but did not differ between sex in L-OC group; in addition, within heifers, L-OC group showed the highest concentration of insulin, whereas within bulls we observed the highest values in H-OC (Figure 3F).

Pairwise correlations between all the included parameters are reported in Table 4. Hepatic enzymes showed significant positive correlations among them and with CK, urea, and TCHO. CK was also positively correlated with TG. TBIL was positively correlated with TG as well, but negatively correlated to GLU, TCHO, and LDH. Lastly, we observed a negative correlation of insulin with glucose, but a positive correlation with AST, LDH, urea, and TCHO.

4. Discussion

Olive by-products, including olive cake (OC), have raised the attention of the scientific community for their possible use as livestock diet integration, giving the opportunity to reduce feed costs while improving product quality and sustainability. Mediterranean countries are among the major producers of olive oil, and the processing of this product generates a large quantity of co-products with a high environmental impact (1–2). To answer to the current need to increase the sustainability of Mediterranean agricultural sectors by implementing solutions which result in a valuable output, and in this case, in terms of benefits for animal feeding from OC utilization.

Several ruminants (Yáñez-Ruiz and Molina-Alcaide, 2007; Awawdeh, 2011; Abbeddou et al., 2011a,b; Estaún et al., 2014; Castellani et al., 2017; Kotsampasi et al., 2017; Awawdeh et al., 2020; Chiofalo B. et al., 2020; Chiofalo V. et al., 2020; Neofytou et al., 2020; Alkhtib et al., 2021; Symeou et al., 2021; Tzamaloukas et al., 2021) and monogastric meat species (Rupić et al., 1999; Paiva-Martins et al., 2014; Parsaei et al., 2014; Ait-Kaki et al., 2018; Reda et al., 2020) have been investigated, but beef cattle appear to be under-represented. Moreover, most of the studies mainly focus on animal performance and/or the final product or the rumen function (Estaún et al., 2014). For this reason, there is little knowledge about the metabolic effect that OC integration might have on beef cattle metabolism, which represents the main subject of this work.

In all the enrolled Limousine beef cattle the serum concentrations of lipids (TG, TCHO), parameters of liver functions associated with energy and protein metabolism (GLU, TBIL, AST, ALT, LDH), renal function (urea), indicators of muscle protein turnover and energy utilization (CK), and lipogenic hormones (insulin) were in line with physiological

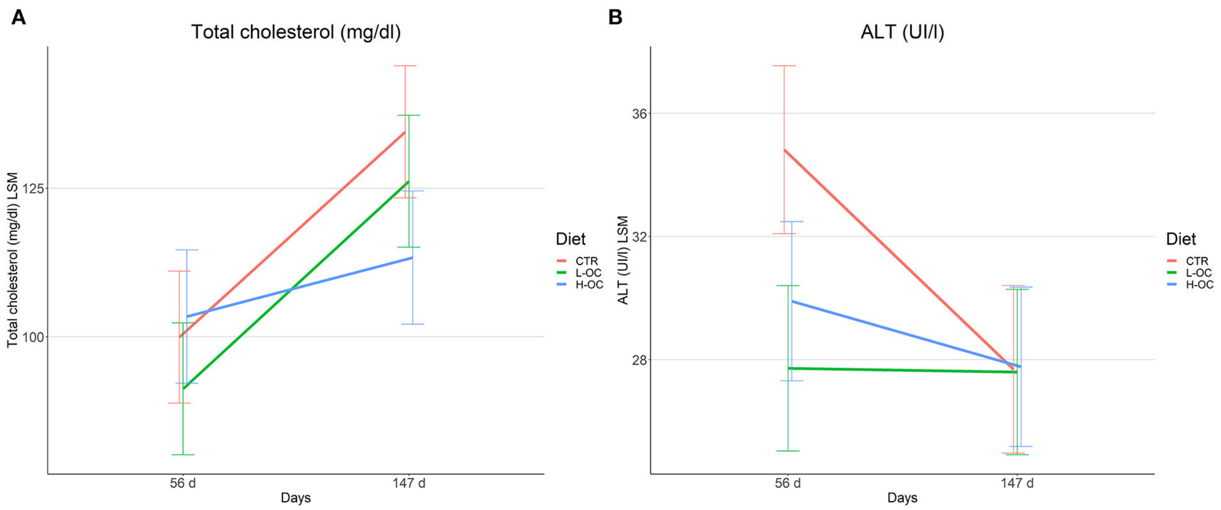


FIGURE 2
Significant effect of the diet x time interaction on total cholesterol **(A)** and ALT **(B)**. The parameters' least square mean (LSM) and standard error are represented for both the sampling times (56 and 147 days) and all the groups with different olive cake inclusions, namely control (CTR, 0%), Low-olive cake (L-OC, 10%), and High-olive cake (H-OC, 15%) groups.

ranges for bovine species (Kaneko et al., 2008), independently from the absence or the 10 or 15% integration of OC in their diet, becoming a relevant result of the current study. Specifically, values of urea and AST were in the range found by Doornenbal et al. (1988) and Gonano et al. (2014) in beef heifers. CK activity was higher than those observed in most studies but still within the range set by Latimer (2011) in cows and in beef heifers.

We also observed that diet or its interaction with sex and/or time of sampling proved to slightly, yet significantly, affect some of these parameters, which are described below.

It is to be considered that, according to our results, the inclusion of the OC did not negatively affect metabolism, as well as the growth of the enrolled animals, consistently with previous studies on beef cattle and lambs (Awawdeh, 2011; Estaún et al., 2014; Kotsampasi et al., 2017; Chiofalo V. et al., 2020; Tzamaloukas et al., 2021). Particularly, no differences were observed in body and carcass weights in heifers. Instead, body weight was higher in CTR bulls, but the carcasses had similar weights independently from the administered diet.

4.1. Lipids (TG, TCHO)

In the present study, growth of animals was characterized by an increase in triglyceridemia and total cholesterolemia. The increase in TCHO concentration can be explained by the marked growth of animals during the finishing phase and the consequent intensification of the anabolic activity of fat and liver metabolism (Van Soest, 1994). Moreover, several studies observed that a high level of TCHO during the early stages of growth is also related to the precocity of puberty attainment (Anderson et al., 2015; Rodríguez-Sánchez et al., 2015) and that TCHO concentrations increase with advancing age in beef cattle, according to the start of puberty and related sexual maturity. Concerning the effect of the diet, we also observed that the increase over time of TCHO was to a lesser extent in the H-OC group only. Accordingly, previous studies investigating olive by-products in sheep diets found no variation or a decrease in TG and TCHO concentrations (El-Tarabany et al., 2018; Awawdeh et al., 2020; Alkhtib et al., 2021). This may be due to the OC's high content in unsaturated fatty acids and phytosterols (Viveros et al., 2009; Cedó et al., 2019).

When considering the effect of sex, heifers showed significant higher TCHO and TG concentrations than bulls. Many aspects of sex differences in physiology arise due to the mechanisms of the sex hormones, including TG and TCHO biology. Estrogen has pleiotropic effects on many tissues and pathways that govern lipid and lipoprotein metabolism and also affects cholesterol efflux capacity (Matthews et al., 2000; Zhu et al., 2018). Heifers may potentially have the capacity to undergo different metabolic adjustments according to their sexual maturity, compared to bulls, as confirmed by the significant effect of age at first service on heifers' plasma concentrations of TG and TCHO observed in cattle and buffalos (Talavera et al., 1985; Wehrman et al., 1991; Ryan et al., 1992; Campanile et al., 2010; Hussein and Abdel-Raheem, 2013). This might explain why we could observe a slight

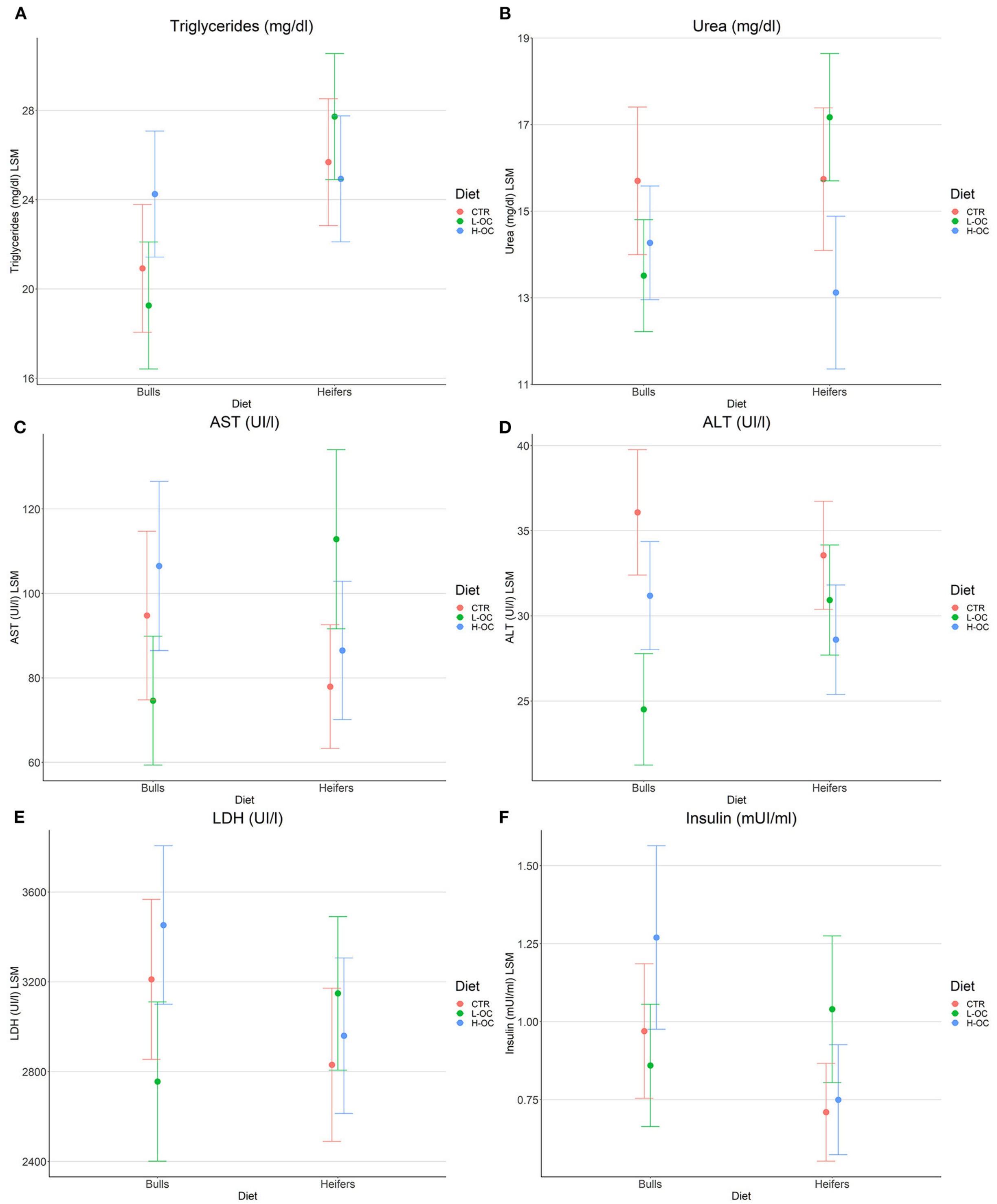


FIGURE 3
Significant effect of the diet x sex interaction on total triglycerides **(A)**, urea **(B)**, AST **(C)**, ALT **(D)**, LDH **(E)**, and insulin **(F)**. The parameters' least square mean (LSM) and standard error are represented for both the sexes and all the groups with different olive cake inclusions, namely control (CTR, 0%), Low-olive cake (L-OC, 10%), and High-olive cake (H-OC, 15%) groups.

10.3389/fsufs.2022.1077363

TABLE 4 Pairwise correlations for all the included blood parameters.

	AST (UI/l)	ALT (UI/l)	LDH (UI/l)	CK (UI/l)	TBIL (mg/dl)	Urea (mg/dl)	GLU (mg/dl)	TCHO (mg/dl)	TG (mg/dl)
ALT (UI/lh)	**0.48**								
	$P < 0.0001$								
LDH (UI/l)	**0.58**	**0.53**							
	$P < 0.0001$	**$P < 0.0001$**							
CK (UI/l)	**0.28**	**0.29**	**0.31**						
	$P = 0.0008$	**$P = 0.0005$**	**$P = 0.0002$**						
TBIL (mg/dl)	−0.02	−0.08	**−0.33**	−0.06					
	$P = 0.7947$	$P = 0.3221$	**$P < 0.0001$**	$P = 0.4631$					
Urea (mg/dl)	**0.30**	**0.26**	**0.29**	0.04	0.03				
	$P = 0.0003$	**$P = 0.0017$**	**$P = 0.0005$**	$P = 0.6708$	$P = 0.7477$				
GLU (mg/dl)	−0.03	0.14	−0.01	0.01	**−0.19**	0.06			
	$P = 0.7168$	$P = 0.0944$	$P = 0.9121$	$P = 0.9037$	**$P = 0.0206$**	$P = 0.5023$			
TCHO (mg/dl)	**0.35**	**0.27**	**0.54**	**0.21**	**−0.2**	**0.20**	−0.07		
	$P < 0.0001$	**$P = 0.0013$**	**$P < 0.0001$**	**$P = 0.0124$**	**$P = 0.0153$**	**$P = 0.0158$**	$P = 0.4353$		
TG (mg/dl)	0.07	0.13	−0.06	**0.18**	**0.37**	0.04	0.09	0.04	
	$P = 0.3929$	$P = 0.1126$	$P = 0.493$	**$P = 0.0325$**	**$P < 0.0001$**	$P = 0.6059$	$P = 0.3006$	$P = 0.6341$	
Insulin (mUI/ml)	**0.41**	0.13	**0.40**	0.07	−0.15	**0.25**	**−0.22**	**0.49**	−0.01
	$P < 0.0001$	$P = 0.1217$	**$P < 0.0001$**	$P = 0.4167$	$P = 0.0784$	**$P = 0.0028$**	**$P = 0.0076$**	**$P < 0.0001$**	$P = 0.8585$

Significant correlations ($P < 0.05$) are reported in bold. TBIL, total bilirubin; GLU, glucose; TCHO, total cholesterol; TG, triglycerides.

difference in TG concentration due to the diet in bulls but not in heifers.

4.2. Total bilirubin

We observed that TBIL concentration increased from 56 to 147 d and was positively related to the OC inclusion. However, it is important to underline that all the measurements remained within the physiological range.

There are few studies reporting the effect of the diet on this parameter, and no study concerns the integration of olive by-products. It is known that, in cattle, a negative energy balance affects fat mobilization and liver function, leading to an increase in TBIL serum concentrations (Mayasari et al., 2019; Marcato et al., 2021; Hisadomi et al., 2022). It has been observed that unsaturated fatty acids, largely present in the OC, reduce bilirubin conjugation, thus increasing its serum concentration (Hargreaves, 1973; Oliveira et al., 2021). In fact, a similar effect was also observed in new-born calves fed with banana extracts (Keivani Rad et al., 2021).

4.3. Urea

The observed significant increase of urea concentrations from 56 to 147 d is consistent with data previously recorded in both beef and dairy cattle (Swali et al., 2008; Brickell et al., 2009; Gonano et al., 2014). A difference in urea concentration was observed in bulls fed with L-OC and H-OC diet, which showed the highest and lowest values, respectively. Instead, heifers showed similar concentrations regardless the OC inclusion. Urea is one of the few blood parameters that was often evaluated in studies regarding the integration of olive by-products in livestock diet, with most of them reporting a decrease in uremia, which supports our results (Yáñez-Ruiz and Molina-Alcaide, 2007; El-Tarabany et al., 2018; Awawdeh et al., 2020; Alkhtib et al., 2021). This effect was associated to a possible reduction in nitrogen intake or protein rumen degradability due to the bind between tannins and dietary proteins (Yáñez-Ruiz and Molina-Alcaide, 2007; Correddu et al., 2020).

4.4. Liver enzymes (AST, ALT, and LDH)

With regard to hepatic enzymes, we observed that ALT was higher in control animals, but the differences among the groups disappeared when we considered the last sampling period. Accordingly, animals of several species, both ruminant (El-Tarabany et al., 2018; Lipińska and Józwik, 2018; Awawdeh et al., 2020; Alkhtib et al., 2021) and monogastric (Paiva-Martins et al., 2014; Parsaei et al., 2014), showed similar or slightly lower ALT activity when fed with olive or chokeberry by-products. It can be hypothesized that this enzyme decreases due to the effect of antioxidants and polyphenols on the liver.

Interestingly, we also observed a similar effect of sex-diet interaction on all the hepatic enzymes. Particularly, lower activity of all of them were measured with the 10% integration (L-OC), in bulls only. Most of the studies on olive by-products administration showed no differences in these parameters (Paiva-Martins et al., 2014; El-Tarabany et al., 2018; Awawdeh et al., 2020; Alkhtib et al., 2021), but the extent of the integration might be important; in fact, in broilers, a small quantity of olive cake has been associated to a decreased AST, whereas a great quantity to increased AST activity (Parsaei et al., 2014). Moreover, a reduction of AST and LDH activities was also recorded in lambs fed with chokeberry by-products (Lipińska and Józwik, 2018). It might be speculated that these alterations depend on a lower diet nitrogen content, which can influence the hepatic metabolism decreasing AST and ALT activities (Puppel and Kuczyńska, 2016).

4.5. Creatin kinase

As well as AST, CK activity was higher in CTR animals than L-OC and H-OC. The CK is an indicator of muscle protein turnover and is also associated with energy utilization (Baird et al., 2012). Its activity can vary according to the time of the day, age, growth rate, and pregnancy (Gonano et al., 2014); nevertheless, in the present study it is possible to exclude the effect of these variables on the changes of CK activity, because animals were homogenous for age, growth rate, time, and physiological conditions.

In addition, elevated CK activity due to the muscle damage, which can be caused by the physical activity-related oxidative stress, can be prevented or reduced by antioxidant supplementation (Ostojic et al., 2008; Wang et al., 2008; Gupta et al., 2009; Marius-Daniel and Stelian Dragomir, 2010; Bentley et al., 2012). For example, red fruit oil, a natural source of antioxidant, showed to decrease significantly the CK activity during exercise when supplemented to mice (Sinaga and Purba, 2018). On this evidence, it is possible to presume that the antioxidants present in the OC contributed to decrease the activity of CK in both L-OC and H-OC. What is more, diets supplemented with olive or chokeberry by-products led to no variation or a decrease of creatin kinase activity, similarly to our study (Lipińska and Józwik, 2018; Awawdeh et al., 2020).

4.6. Glucose and insulin

Insulin is known to accelerate anabolic processes, such as the synthesis of muscular protein contributing to muscle

10.3389/fsufs.2022.1077363

development, and the synthesis and deposition of fat along developmental processes. Insulin is essential for the regulation of glucose and lipid metabolism and also affects growth through its promotion of the uptake of nutrients into body tissues as recorded by Martin et al. (Martin et al., 1984) and as shown by the existence of significant correlations between insulin and glucose, TCHO, TG, AST, and TBIL. On the other hand, glucose is the favored substrate for lipogenic adipocytes in muscle, whereas acetate is preferred in subcutaneous adipocytes and as precursor of *de novo* fatty acid synthesis (Smith and Crouse, 1984; Gilbert et al., 2003; Ladeira et al., 2016; Bionaz et al., 2020).

In the present study, insulin was higher in bulls and increased from 56 to 147 d, whereas the opposite was true for glucose, in accordance with the literature (Roy et al., 1983; Gray et al., 1986; Beeby et al., 1988; Plouzek and Trenkle, 1991; Shingu et al., 2001). Bulls, in fact, show higher concentrations of insulin-like growth factor 1, growth hormone, and insulin compared with cows, probably due to the effect of sex-dependent steroid, and this might partially explain their increased growth rate (Ronge and Blum, 1989; Plouzek and Trenkle, 1991; Sirotkin et al., 2002). Fat accumulation in different depots is also sexually dimorphic: in humans, men accumulate more visceral fat, whereas women accumulate more subcutaneous fat and have a higher overall percentage of body fat. There is also evidence indicating that insulin sensitivity differs between males and females (Sirotkin et al., 2002; Macotela et al., 2009). In mice, it was observed that the intra-abdominal depot is regulated by physiological levels of sex steroid and that female mice are more insulin-sensitive that males and their adipocyte show higher expression of glucose and lipid metabolism genes (Mittendorfer, 2005). However, how insulin action differs between males and females and how these differences account for a sex-specific regulation of adipose tissue development and function are not completely clear.

In the present study, we observed a similar insulin concentration in heifers and bulls of the L-OC group, even if diet or its interaction had no effect on glycemia. It should be noticed that, as far as we know, this is the first study analyzing the effect of an olive by-product inclusion on insulin in livestock, but on the other hand it has been demonstrated the phenols contained in olive leaves have a hypoglycemic effect in several species (Parsaei et al., 2014; Ait-Kaki et al., 2018; Lipińska and Józwik, 2018; Alkhtib et al., 2021). Moreover, it is known that a diet rich in carbohydrates tends to increase insulin (Mori et al., 2007) and that glucose kinetics is influenced by the intake of nitrogen and nutrients as well as the fasting length (Brickell et al., 2009; Zanton and Heinrichs, 2017); therefore, we cannot exclude that other mechanisms can be involved in the observed insulin alteration.

5. Conclusions

In the present study we demonstrated that olive cake inclusion in shows no detrimental effect on beef cattle performance and metabolism, according to several blood parameters analyzed at different time points. However, small changes in some analytes have been observed in groups fed with different amount of olive cake, sometimes with different effects in heifers and bulls or at different growing stages, opening the possibility of further research on this topic. Moreover, we provided data about the metabolic profile of beef cattle in the context of diet supplemented with olive cake, improving knowledge about the physiological characterization of these animals at different stages of development. According to the economic analysis, profitability level could be considered interesting, and it should be taken into account in Mediterranean regions. In this sense, in the last years there has been new research exploring the possibilities of further use of the olive residues, like the olive cake, to obtain a valuable outcome on the physiological responses of ruminants, also in terms of endocrine and metabolic adaptations.

Therefore, according to our results, we support an olive cake integration up to 15% of the concentrate in beef cattle diet, thus leading to several advantages also in terms of feed costs and environmental sustainability, as a model of circular economy.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal study was reviewed and approved by Ethical Committee of the Department of Veterinary Science, University of Messina, Italy (code 041/2020). Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

EF and LL: conceptualization. VC: methodology. PC: software. AB and VL: validation. AB and MO: formal analysis. VL: investigation. AB, PC, AA, and VL: data curation. EF: writing—original draft preparation. EF, AB, and VL: writing—review and editing. AB and LL: visualization. LL: supervision, project administration, and funding acquisition.

All authors have read and agreed to the published version of the manuscript.

Funding

This study was funded by P.O. FESR SICILIA 2014/2020. Obiettivo Tematico 1—Ricerca, Sviluppo Tecnologico e Innovazione Obiettivo specifico 1.1—Incremento dell'attività di innovazione delle imprese Azione 1.1.5—Sostegno all'avanzamento tecnologico delle imprese attraverso il finanziamento di linee pilota e azioni di validazione precoce dei prodotti e di dimostrazione su larga scala. Project BIOTRAK. Grant No. 08SR1091000150–CUP G69J18001000007 (principal investigator: LL).

Acknowledgments

Authors wish to thank Feed Manufacturing Industry Dipasquale srl (Avola—SR, IT) for the production of feed, Oil mill Industry Consoli (Adrano—CT, IT) for the production of destoned olive cake, and Spadola Farm for guesting the in-field trials.

Conflict of interest

Author VC was employed by Consortium of Research for Meat Chain and Agrifood (CoRFilCarni).

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abbeddou, S., Rischkowsky, B., Hilali, M. E.-D., Hess, H. D., and Kreuzer, M. (2011a). Influence of feeding mediterranean food industry by-products and forages to awassi sheep on physicochemical properties of milk, yoghurt and cheese. *J. Dairy Res.* 78, 426–435. doi: 10.1017/S0022029911000665

Abbeddou, S., Rischkowsky, B., Richter, E. K., Hess, H. D., and Kreuzer, M. (2011b). Modification of milk fatty acid composition by feeding forages and agro-industrial byproducts from dry areas to awassi sheep. *J. Dairy Sci.* 94, 4657–4668. doi: 10.3168/jds.2011-4154

Ait-Kaki, A., Diaw, M., Geda, F., and Moula, N. (2018). Effects of artemisia herba-alba or olive leaf (*Olea europaea*) powder supplementation on growth performance, carcass yield, and blood biochemical parameters in broilers. *Vet. World* 11, 1624–1629. doi: 10.14202/vetworld.2018.1624-1629

Al-Harthi, M. A. (2016). The efficacy of using olive cake as a by-product in broiler feeding with or without yeast. *Ital. J. Anim. Sci.* 15, 512–520. doi: 10.1080/1828051X.2016.1194173

Alkhtib, A., Muna, M., Burton, E., Wamatu, J., Darag, M., Alkhaled, E., et al. (2021). Effect of olive tree leaves and twigs on intake, digestibility, growth performance and blood variables of shami goats. *Vet. Med. Sci.* 7, 908–914. doi: 10.1002/vms3.419

Anderson, J. L., Kalscheur, K. F., Clapper, J. A., Perry, G. A., Keisler, D. H., Garcia, A. D., et al. (2015). Feeding fat from distillers dried grains with solubles to dairy heifers: II. Effects on metabolic profile. *J. Dairy Sci.* 98, 5709–5719. doi: 10.3168/jds.2014-9163

Awawdeh, M. S. (2011). Alternative feedstuffs and their effects on performance of awassi sheep: a review. *Trop. Anim. Health Prod.* 43, 1297–1309. doi: 10.1007/s11250-011-9851-z

Awawdeh, M. S., Dager, H. K., and Obeidat, B. S. (2020). Dietary inclusion of alternative feedstuffs had no negative effects on hematological and biochemical parameters of growing awassi lambs. *Trop. Anim. Health Prod.* 52, 2157–2162. doi: 10.1007/s11250-020-02236-3

Awawdeh, M. S., and Obeidat, B. S. (2013). Treated olive cake as a non-forage fiber source for growing awassi lambs: effects on nutrient intake, rumen and urine ph, performance, and carcass yield. *Asian Austral. J. Anim. Sci.* 26, 661–667. doi: 10.5713/ajas.2012.12513

Baird, M. F., Graham, S. M., Baker, J. S., and Bickerstaff, G. F. (2012). Creatine-kinase- and exercise-related muscle damage implications for muscle performance and recovery. *J. Nutr. Metab.* 2012, 960363. doi: 10.1155/2012/960363

Beeby, J. M., Haresign, W., and Swan, H. (1988). Endogenous hormone and metabolite concentrations in different breeds of beef steer on two systems of production. *Anim. Sci.* 47, 231–244. doi: 10.1017/S0003356100003317

Bentley, D. J., Dank, S., Coupland, R., Midgley, A., and Spence, I. (2012). Acute antioxidant supplementation improves endurance performance in trained athletes. *Res. Sports Med.* 20, 1–12. doi: 10.1080/15438627.2011.608050

Berbel, J., and Posadillo, A. (2018). Review and analysis of alternatives for the valorisation of agro-industrial olive oil by-products. *Sustainability* 10, 237. doi: 10.3390/su10010237

Bionaz, M., Vargas-Bello-Pérez, E., and Busato, S. (2020). Advances in fatty acids nutrition in dairy cows: from gut to cells and effects on performance. *J. Anim. Sci. Biotechnol.* 11, 110. doi: 10.1186/s40104-020-00512-8

Branciari, R., Ranucci, D., Miraglia, D., Urbani, S., Esposto, S., Servili, M., et al. (2015). Effect of dietary treatment with olive oil by-product (olive cake) on physico-chemical, sensory and microbial characteristics of beef during storage. *Ital. J. Food Saf.* 4, 5496. doi: 10.4081/ijfs.2015.5496

Brickell, J. S., Bourne, N., McGowan, M. M., and Wathes, D. C. (2009). Effect of growth and development during the rearing period on the subsequent fertility of nulliparous Holstein-Friesian heifers. *Theriogenology*. 72, 408–416. doi: 10.1016/j.theriogenology.2009.03.015

Campanile, G., Baruselli, P. S., Vecchio, D., Prandi, A., Neglia, G., Carvalho, N. A. T., et al. (2010). Growth, metabolic status and ovarian function in buffalo (*Bubalus bubalis*) heifers fed a low energy or high energy diet. *Anim. Reprod. Sci.* 122, 74–81. doi: 10.1016/j.anireprosci.2010.07.005

Castellani, F., Vitali, A., Bernardi, N., Marone, E., Palazzo, F., Grotta, L., et al. (2017). Dietary supplementation with dried olive pomace in dairy cows modifies the composition of fatty acids and the aromatic profile in milk and related cheese. *J. Dairy Sci.* 100, 8658–8669. doi: 10.3168/jds.2017-12899

Cedó, L., Farràs, M., Lee-Rueckert, M., and Escolà-Gil, J. C. (2019). Molecular insights into the mechanisms underlying the cholesterol-lowering effects of phytosterols. *Curr. Med. Chem.* 26, 6704–6723. doi: 10.2174/0929867326666190822154701

Chiofalo, B., di Rosa, A. R., Lo Presti, V., Chiofalo, V., and Liotta, L. (2020). Effect of supplementation of herd diet with olive cake on the composition profile of milk and on the composition, quality and sensory profile of cheeses made therefrom. *Animals* 10, 977. doi: 10.3390/ani10060977

Chiofalo, B., Liotta, L., Zumbo, A., and Chiofalo, V. (2004). Administration of olive cake for ewe feeding: effect on milk yield and composition. *Small Rumin. Res.* 55, 169–176. doi: 10.1016/j.smallrumres.2003.12.011

Chiofalo, V., Liotta, L., Lo Presti, V., Gresta, F., Di Rosa, A. R., and Chiofalo, B. (2020). Effect of dietary olive cake supplementation on performance, carcass characteristics, and meat quality of beef cattle. *Animals* 10, 1176. doi: 10.3390/ani10071176

Correddu, F., Lunesu, M. F., Buffa, G., Atzori, A. S., Nudda, A., Battacone, G., et al. (2020). Can agro-industrial by-products rich in polyphenols be advantageously used in the feeding and nutrition of dairy small ruminants? *Animals* 10, 131. doi: 10.3390/ani10010131

Council of the European Union (2010). *Directive 2010/63/EU of the European Parliament and of the Council*. Council of the European Union.

de Evan, T., Cabezas, A., de la Fuente, J., and Carro, M. D. (2020). Feeding agroindustrial byproducts to light lambs: influence on growth performance, diet digestibility, nitrogen balance, ruminal fermentation, and plasma metabolites. *Animals* 10, 600. doi: 10.3390/ani10040600

Doornenbal, H., Tong, A. K., and Murray, N. L. (1988). Reference values of blood parameters in beef cattle of different ages and stages of lactation. *Can. J. Vet. Res.* 52, 99–105.

El Otmani, S., Chebli, Y., Taminiau, B., Chentouf, M., Hornick, J.-L., and Cabaraux, J.-F. (2021). Effect of olive cake and cactus cladodes incorporation in goat kids' diet on the rumen microbial community profile and meat fatty acid composition. *Biology* 10, 1237. doi: 10.3390/biology10121237

El-Tarabany, A., Mostafa, M., and Mohamed, A. (2018). Effect of dietary olive cake on reproductive and physiological traits of native pregnant ewes. *Arab. J. Nucl. Sci. Applic.* 51, 135–142. doi: 10.21608/ajnsa.2018.12788

Espeso, J., Isaza, A., Lee, J. Y., Sörensen, P. M., Jurado, P., Avena-Bustillos, R. J., et al. (2021). Olive leaf waste management. *Front. Sustain. Food Syst*. 5, 660582. doi: 10.3389/fsufs.2021.660582

Estaún, J., Dosil, J., Al Alami, A., Gimeno, A., and de Vega, A. (2014). Effects of including olive cake in the diet on performance and rumen function of beef cattle. *Anim. Prod. Sci*. 54, 1817. doi: 10.1071/AN14352

Foti, P., Pino, A., Romeo, F. V., Vaccalluzzo, A., Caggia, C., Randazzo, C. L., et al. (2022). Olive pomace and pâté olive cake as suitable ingredients for food and feed. *Microorganisms* 10, 237. doi: 10.3390/microorganisms10020237

Ghanbari, R., Anwar, F., Alkharfy, K. M., Gilani, A.-H., and Saari, N. (2012). Valuable nutrients and functional bioactives in different parts of olive (*Olea europaea* L.)—a review. *Int. J. Mol. Sci*. 13, 3291–3340. doi: 10.3390/ijms13033291

Gilbert, C. D., Lunt, D. K., Miller, R. K., and Smith, S. B. (2003). Carcass, sensory, and adipose tissue traits of brangus steers fed casein-formaldehyde-protected starch and/or canola lipid1. *J. Anim. Sci*. 81, 2457–2468. doi: 10.2527/2003.81102457x

Gonano, C. V., Montanholi, Y. R., Schenkel, F. S., Smith, B. A., Cant, J. P., Miller, S. P., et al. (2014). The relationship between feed efficiency and the circadian profile of blood plasma analytes measured in beef heifers at different physiological stages. *Animal* 8, 1684–1698. doi: 10.1017/S1751731114001463

Gray, D. G., Unruh, J. A., Dikeman, M. E., and Stevenson, J. S. (1986). Implanting young bulls with zeranol from birth to four slaughter ages: III. Growth performance and endocrine aspects. *J. Anim. Sci.* 63, 747–756. doi: 10.2527/jas1986.633747x

Gupta, C., Gupta, P. H., and Singh, B. (2009). Effect of vitamin supplementation on exercise induced oxidative stress in trained elite indian cyclists. *Am. J. Biomed. Sci*. 1, 166–170. doi: 10.5099/aj090200166

Hargreaves, T. (1973). Effect of fatty acids on bilirubin conjugation. *Arch. Dis. Child*. 48, 446–450. doi: 10.1136/adc.48.6.446

Hisadomi, S., Haruno, A., Fujieda, T., Sugino, T., and Oba, M. (2022). Effects of rumen-protected glutamate supplementation during the periparturient period on digestibility, inflammation, metabolic responses, and performance in dairy cows. *J. Dairy Sci*. 105, 3129–3141. doi: 10.3168/jds.2021-21357

Hussein, H. A., and Abdel-Raheem, S. M. (2013). Effect of feed intake restriction on reproductive performance and pregnancy rate in Egyptian buffalo heifers. *Trop. Anim. Health Prod.* 45, 1001–1006. doi: 10.1007/s11250-012-0324-9

Joven, M., Pintos, E., Latorre, M. A., Suárez-Belloch, J., Guada, J. A., Fondevila, M., et al. (2014). Effect of replacing barley by increasing levels of olive cake in the diet of finishing pigs: Growth performances, digestibility, carcass, meat and fat quality. *Anim. Feed Sci. Technol.* 197, 185–193. doi: 10.1016/j.anifeedsci.2014.08.007

Kaneko, J. J., Harvey, J. W., and Bruss, M. L. (2008). *Clinical Biochemistry of Domestic Animals, 6th Edn*. San Diego, CA: Academic Press.

Keivani Rad, N., Mohri, M., Seifi, H. A., and Haghparast, A. (2021). Supplementation of overripe pulp extract and green peel extract or powder of banana fruit peel (musa. cavendish) to diets of neonatal dairy calves: effects on haematological, immunological and performance characteristics. *Vet. Med. Sci*. 7, 876–887. doi: 10.1002/vms3.429

Keleş, G. (2015). The nutritive and feeding value of olive cake for ruminants. *Turk. J. Agric. Food Sci. Technol.* 3, 780. doi: 10.24925/turjaf.v3i10.780-789.435

Kotsampasi, B., Bampidis, V. A., Tsiaousi, A., Christodoulou, C., Petrotos, K., Amvrosiadis, I., et al. (2017). Effects of dietary partly destoned exhausted olive cake supplementation on performance, carcass characteristics and meat quality of growing lambs. *Small Rumin. Res.* 156, 33–41. doi: 10.1016/j.smallrumres.2017.08.013

Ladeira, M., Schoonmaker, J., Gionbelli, M., Dias, J., Gionbelli, T., Carvalho, J., et al. (2016). Nutrigenomics and beef quality: a review about lipogenesis. *Int. J. Mol. Sci*. 17, 918. doi: 10.3390/ijms17060918

Latimer, K. S. (2011). *Duncan and Prasse's Veterinary Laboratory Medicine: Clinical Pathology, 5th Edn*. West Sussex: Wiley-Blackwell.

Liotta, L., Chiofalo, V., Lo Presti, V., and Chiofalo, B. (2019). *In vivo* performances, carcass traits, and meat quality of pigs fed olive cake processing waste. *Animals* 9, 1155. doi: 10.3390/ani9121155

Lipińska, P., and Józwik, A. (2018). Hepatoprotective, hypoglycemic, and hypolipidemic effect of chokeberry pomace on polish merino lambs. *Anim. Biotechnol*. 29, 136–141. doi: 10.1080/10495398.2017.1330209

Macotela, Y., Boucher, J., Tran, T. T., and Kahn, C. R. (2009). Sex and depot differences in adipocyte insulin sensitivity and glucose metabolism. *Diabetes* 58, 803–812. doi: 10.2337/db08-1054

Marcato, F., van den Brand, H., Jansen, C. A., Rutten, V. P. M. G., Kemp, B., Engel, B., et al. (2021). Effects of pre-transport diet, transport duration and transport condition on immune cell subsets, haptoglobin, cortisol and bilirubin in young veal calves. *PLoS ONE* 16, e0246959. doi: 10.1371/journal.pone.0246959

Marius-Daniel, R., and Stelian Dragomir, C. (2010). The effect of acute physical exercise on the antioxidant status of the skeletal and cardiac muscle in the Wistar rat. *Rom. Biotechnol. Lett*. 15, 56–61.

Martin, R. J., Ramsay, T. G., and Harris, R. B. S. (1984). Central role of insulin in growth and development. *Domest. Anim. Endocrinol.* 1, 89–104. doi: 10.1016/0739-7240(84)90024-9

Matthews, J., Celius, T., Halgren, R., and Zacharewski, T. (2000). Differential estrogen receptor binding of estrogenic substances: a species comparison. *J. Steroid Biochem. Mol. Biol.* 74, 223–234. doi: 10.1016/S0960-0760(00)00126-6

Mayasari, N., Trevisi, E., Ferrari, A., Kemp, B., Parmentier, H. K., van Knegsel, A. T. M., et al. (2019). Relationship between inflammatory biomarkers and oxidative stress with uterine health in dairy cows with different dry period lengths. *Transl. Anim. Sci*. 3, 607–619. doi: 10.1093/tas/txz040

Mele, M., Serra, A., Pauselli, M., Luciano, G., Lanza, M., Pennisi, P., et al. (2014). The use of stoned olive cake and rolled linseed in the diet of intensively reared lambs: effect on the intramuscular fatty-acid composition. *Animal* 8, 152–162. doi: 10.1017/S1751731113001924

Mittendorfer, B. (2005). Insulin resistance: sex matters. *Curr. Opin. Clin. Nutr. Metab. Care*. 8, 367–372. doi: 10.1097/01.mco.0000172574.64019.98

Mori, A., Urabe, S., Asada, M., Tanaka, Y., Tazaki, H., Yamamoto, I., et al. (2007). Comparison of plasma metabolite concentrations and enzyme activities in beef cattle raised by different feeding systems in Korea, Japan and New Zealand. *J. Vet. Med. Ser. A* 54, 342–345. doi: 10.1111/j.1439-0442.2007.00964.x

Neofytou, M. C., Miltiadou, D., Sfakianaki, E., Constantinou, C., Symeou, S., Sparaggis, D., et al. (2020). The use of ensiled olive cake in the diets of Friesian cows increases beneficial fatty acids in milk and Halloumi cheese and alters the expression of SREBF1 in adipose tissue. *J. Dairy Sci*. 103, 8998–9011. doi: 10.3168/jds.2020-18235

Oliveira, M. X. S., Palma, A. S., Reis, B. R., Franco, C. S. R., Marconi, A. P. S., Shiozaki, F. A., et al. (2021). Inclusion of soybean and linseed oils in the diet of lactating dairy cows makes the milk fatty acid profile nutritionally healthier for the human diet. *PLoS ONE* 16, e0246357. doi: 10.1371/journal.pone.0246357

Ostojic, S. M., Stojanovic, M. D., Djordjevic, B., Jourkesh, M., and Vasiljevic, N. (2008). The effects of a 4-week coffeeberry supplementation on antioxidant status, endurance, and anaerobic performance in college athletes. *Res. Sports Med*. 16, 281–294. doi: 10.1080/15438620802523345

Paiva-Martins, F., Ribeirinha, T., Silva, A., Gonçalves, R., Pinheiro, V., Mourão, J. L., et al. (2014). Effects of the dietary incorporation of olive leaves on growth performance, digestibility, blood parameters and meat quality of growing pigs. *J. Sci. Food Agric*. 94, 3023–3029. doi: 10.1002/jsfa.6650

Parsaei, S., Amini, Z., and Houshmand, M. (2014). Effects of olive leaf on blood metabolites and humoral immunity response of broiler chickens. *Int. J. Adv. Biol. Biomed. Res*. 2, 741–751.

Plouzek, C. A., and Trenkle, A. (1991). Insulin-like growth factor-I concentrations in plasma of intact and castrated male and female cattle at four ages. *Domest. Anim. Endocrinol*. 8, 73–79. doi: 10.1016/0739-7240(91)90041-H

Puppel, K., and Kuczyńska, B. (2016). Metabolic profiles of cow's blood; a review. *J. Sci. Food Agric*. 96, 4321–4328. doi: 10.1002/jsfa.7779

Reda, F. M., El-Kholy, M. S., Abd El-Hack, M. E., Taha, A. E., Othman, S. I., Allam, A. A., et al. (2020). Does the use of different oil sources in quail diets impact their productive and reproductive performance, egg quality, and blood constituents? *Poult. Sci*. 99, 3511–3518. doi: 10.1016/j.psj.2020.03.054

Rodríguez-Sánchez, J. A., Sanz, A., Tamanini, C., and Casasús, I. (2015). Metabolic, endocrine, and reproductive responses of beef heifers submitted to different growth strategies during the lactation and rearing periods. *J. Anim. Sci*. 93, 3871–3885. doi: 10.2527/jas.2015-8994

Ronge, H., and Blum, J. W. (1989). Insulin-like growth factor I binding proteins in dairy cows, calves and bulls. *Acta Endocrinol*. 121, 153–160. doi: 10.1530/acta.0.1210153

Roy, J. H. B., Hart, I. C., Gillies, C. M., Stobo, I. J. F., Ganderton, P., Perfitt, M. W., et al. (1983). A comparison of preruminant bull calves of the Hereford × Friesian, Aberdeen Angus × Friesian and Friesian breeds. *Anim. Sci*. 36, 237–251. doi: 10.1017/S1357729800001302

Rupić, V., Bozikov, V., Bozac, R., Muzic, S., Vranesić, N., and Dikić, M. (1999). Effect of feeding olive by-products on certain blood parameters and serum enzyme activities of fattening rabbits. *Acta Vet. Hung*. 47, 65–75. doi: 10.1556/avet.47.1999.1.6

Ryan, D. P., Spoon, R. A., and Williams, G. L. (1992). Ovarian follicular characteristics, embryo recovery, and embryo viability in heifers fed high-fat diets and treated with follicle-stimulating hormone. *J. Anim. Sci*. 70, 3505–3513. doi: 10.2527/1992.70113505x

Salomone, R., and Ioppolo, G. (2012). Environmental impacts of olive oil production: a life cycle assessment case study in the province of Messina (Sicily). *J. Clean. Prod*. 28, 88–100. doi: 10.1016/j.jclepro.2011.10.004

Shingu, H., Hodate, K., Kushibiki, S., Ueda, Y., Watanabe, A., Shinoda, M., et al. (2001). Profiles of growth hormone and insulin secretion, and glucose response to insulin in growing Japanese Black heifers (beef type): comparison with Holstein heifers (dairy type). *Comp. Biochem. Physiol. C. Toxicol. Pharmacol*. 130, 259–270. doi: 10.1016/S1532-0456(01)00249-6

Sinaga, F. A., and Purba, P. H. (2018). The influence of red fruit oil on creatin kinase level at maximum physical activity. *J. Phys. Conf. Ser*. 970, 012007. doi: 10.1088/1742-6596/970/1/012007

Sirotkin, A., Svetlanská, M., Sommer, A., Makarevich, A., Szakács, J., and Poláciková, M. (2002). Are IGF-I, thyroid hormone and metabolite concentrations in calf plasma associated with growth rate, sex and age? *J. Anim. Feed Sci*. 11, 265–275. doi: 10.22358/jafs/67811/2002

Smith, S. B., and Crouse, J. D. (1984). Relative contributions of acetate, lactate and glucose to lipogenesis in bovine intramuscular and subcutaneous adipose tissue. *J. Nutr*. 114, 792–800. doi: 10.1093/jn/114.4.792

Swali, A., Cheng, Z., Bourne, N., and Wathes, D. C. (2008). Metabolic traits affecting growth rates of pre-pubertal calves and their relationship with subsequent survival. *Domest. Anim. Endocrinol*. 35, 300–313. doi: 10.1016/j.domaniend.2008.06.005

Symeou, S., Miltiadou, D., Constantinou, C., Papademas, P., and Tzamaloukas, O. (2021). Feeding olive cake silage up to 20% of DM intake in sheep improves lipid quality and health-related indices of milk and ovine halloumi cheese. *Trop. Anim. Health Prod*. 53, 229. doi: 10.1007/s11250-021-02674-7

Talavera, F., Park, C. S., and Williams, G. L. (1985). Relationships among dietary lipid intake, serum cholesterol and ovarian function in holstein heifers. *J. Anim. Sci*. 60, 1045–1051. doi: 10.2527/jas1985.6041045x

The European Agency for the Evaluation of Medicinal Products (2000). *Guideline on Good Clinical Practices*. London: The European Agency for the Evaluation of Medicinal Products.

Tzamaloukas, O., Neofytou, M. C., and Simitzis, P. E. (2021). Application of olive by-products in livestock with emphasis on small ruminants: implications on rumen function, growth performance, milk and meat quality. *Animals* 11, 531. doi: 10.3390/ani11020531

Van Soest, P. J. (1994). *Nutritional Ecology of the Ruminant, 2nd edn*. Itacha, NY: Cornell University Press. doi: 10.7591/9781501732355

Vargas-Bello-Pérez, E., Vera, R. R., Aguilar, C., Lira, R., Peña, I., Fernández, J., et al. (2013). Feeding olive cake to ewes improves fatty acid profile of milk and cheese. *Anim. Feed Sci. Technol*. 184, 94–99. doi: 10.1016/j.anifeedsci.2013.05.016

Vastolo, A., Calabró, A., Liotta, L., Musco, N., Di Rosa, A. R., Cutrignelli, M. I., et al. (2019). *In vitro* fermentation and chemical characteristics of mediterranean by-products for swine nutrition. *Animals* 9, 556. doi: 10.3390/ani9080556

Viveros, A., Ortiz, L. T., Rodríguez, M. L., Rebolé, A., Alzueta, C., Arija, I., et al. (2009). Interaction of dietary high-oleic-acid sunflower hulls and different fat sources in broiler chickens. *Poult. Sci*. 88, 141–151. doi: 10.3382/ps.2008-00226

Wang, L., Zhang, H. L., Lu, R., Zhou, Y. J., Ma, R., Lv, J. Q., et al. (2008). The decapeptide CMS001 enhances swimming endurance in mice. *Peptides* 29, 1176–1182. doi: 10.1016/j.peptides.2008.03.004

Wehrman, M. E., Welsh, T. H., and Williams, G. L. (1991). Diet-induced hyperlipidemia in cattle modifies the intrafollicular cholesterol environment, modulates ovarian follicular dynamics, and hastens the onset of postpartum luteal activity. *Biol. Reprod*. 45, 514–522. doi: 10.1095/biolreprod45.3.514

Yáñez Ruiz, D. R., Moumen, A., Martín García, A. I., and Molina Alcaide, E. (2004). Ruminal fermentation and degradation patterns, protozoa population, and urinary purine derivatives excretion in goats and wethers fed diets based on two-stage olive cake: effect of PEG supply1. *J. Anim. Sci*. 82, 2023–2032. doi: 10.2527/2004.8272023x

Yáñez-Ruiz, D. R., and Molina-Alcaide, E. (2007). A comparative study of the effect of two-stage olive cake added to alfalfa on digestion and nitrogen losses in sheep and goats. *Animal* 1, 227–232. doi: 10.1017/S1751731107340032

Zanton, G. I., and Heinrichs, A. J. (2017). Short communication: glucose kinetics in dairy heifers limit-fed a low- or high-forage ration at 4 levels of nitrogen intake. *J. Dairy Sci*. 100, 3718–3724. doi: 10.3168/jds.2016-12037

Zhu, L., Shi, J., Luu, T. N., Neuman, J. C., Trefts, E., Yu, S., et al. (2018). Hepatocyte estrogen receptor alpha mediates estrogen action to promote reverse cholesterol transport during western-type diet feeding. *Mol. Metab*. 8, 106–116. doi: 10.1016/j.molmet.2017.12.012

Zilio, D. M., Bartocci, S., di Giovanni, S., Servili, M., Chiariotti, A., Terramoccia, S., et al. (2015). Evaluation of dried stoned olive pomace as supplementation for lactating Holstein cattle: effect on milk production and quality. *Anim. Prod. Sci*. 55, 185. doi: 10.1071/AN14254

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 22 December 2022
DOI 10.3389/fsufs.2022.1035357

Check for updates

OPEN ACCESS

EDITED BY
Claudio Bellia,
University of Catania, Italy

REVIEWED BY
Carla Zarbà,
University of Catania, Italy
Ho Wai Shin,
University of Technology Malaysia, Malaysia

*CORRESPONDENCE
Adele Finco
a.finco@univpm.it

†These authors have contributed equally to this work and share first authorship

SPECIALTY SECTION
This article was submitted to Waste Management in Agroecosystems, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 02 September 2022
ACCEPTED 07 December 2022
PUBLISHED 22 December 2022

CITATION
Bentivoglio D, Chiaraluce G and Finco A (2022) Economic assessment for vegetable waste valorization through the biogas-biomethane chain in Italy with a circular economy approach.
Front. Sustain. Food Syst. 6:1035357.
doi: 10.3389/fsufs.2022.1035357

Economic assessment for vegetable waste valorization through the biogas-biomethane chain in Italy with a circular economy approach

Deborah Bentivoglio†, Giulia Chiaraluce† and Adele Finco*

Department of Agricultural, Food and Environmental Sciences (D3A), Università Politecnica delle Marche, Ancona, Italy

The current geo-political framework and the environmental concern about pollution and global warming are leading Europe to rethink its energy production, moving forward to the incentivization the renewable energy market. In this scenario, the use of waste from the agri-food sector shows a huge potentiality to enhance the transition in line with the circular economy principles. Biogas production represents an environmental friendly strategy to successfully recover large amounts of waste and by-products to produce renewable energy. Furthermore, in light of the rising need of green biofuels, biogas can be converted into biomethane, allowing the implementation of a full circular model. The objective of this paper is to perform an economic assessment to evaluate whether the upgrading of an existing biogas plant, in which the diet includes also vegetable waste from a plant producing frozen vegetables, could be profitable considering different scenarios, to reach a sustainable circular model. The analysis will be conducted through the Discounted Cash Flow method, considering four main indexes: NPV, DPBT, IRR, and PI. The results highlight the unprofitability of the biogas-biomethane chain if the upgrading system is performed maintaining the same characteristics of the starting plant. On the other hand, if changes in the digester's diet occur, the investment becomes immediately profitable in the considered time-span. The circular economy model is not completely accomplished, as profitability can only be reached if silage maize is partially kept as feedstock. Moreover, the conversion of the plant is not economically feasible if an adequate subsidy is not provided. The economic assessment of the upgrading system for biogas to biomethane is an essential element to be provided to the agribusiness entrepreneurs, as they need all the relevant economic aspects to decide to invest and adopt this solution to establish an innovative circular business model in agriculture.

KEYWORDS

circular economy, vegetable waste, biogas upgrading, biomethane, sustainability, economic analysis, renewable energy, Italy

1. Introduction

The global concern about climate change, fossil fuel depletion, and the increasing prices of energy have resulted in an augmented pressure on national economies, leading policy makers to focalize on alternative innovative ways to produce energy, such as renewable fuels (Barbera et al., 2019; Khan et al., 2021; Naquash et al., 2022). Despite the increased interest in producing green energy, Europe is still not able to declare independence from energy imports of oil, gas, and solid fossil fuels. This situation, combined with the instable political framework, should lead to a reconsideration of the energy system as a whole. In the past, commercially available biofuels were produced from energy crops, creating a controversial condition where most of the feedstock were also important globally traded food commodities (Finco, 2012; Bentivoglio et al., 2014). To try to overcome this problematic, an alternative sustainable energetic feedstock could be represented by biomass residues and waste products from agriculture, agro-industries generated waste, forest by-products, and municipal solid waste (Ambaye et al., 2021). In addition, it is necessary to follow eco-friendly and carbon-neutral approaches in order to encourage the transition from the traditional linear model to the circular one, to overcome the current energy crisis and support the sustainable market position of renewable energies (Abokersh et al., 2021; Cusenza et al., 2021; González-Arias et al., 2022; Jain et al., 2022), in line with the Sustainable Development Goals and the European Green Deal. According to the Ellen MacArthur Foundation (2013), "circular economy represents an economic system based on closed loops, in which raw materials and products keep their quality and value for the longest time as possible, and systems are fueled by renewable energy sources".

In this scenario, the agri-food sector has a huge potential in the context of a circular economy, from the efficient management of resources, valorization and reuse of by-products and wastes, as well as the production of bioenergy and bioproducts through the adoption of sustainable production models (Teixeira, 2018; Chiaraluce et al., 2021). There is a general consensus on the fact that reducing food waste has great potential to enhance food security, strengthen the sustainability of the systems and reduce the economic costs (Vilariño et al., 2017). According to the circular approach and the waste hierarchy, waste management should not only focus on waste prevention, but since some types of processing waste are inevitable, they should be recovered and valorized for alternative solutions like nutrients extraction, animal feeding, or renewable energy production, thus reducing the dependence from fossil fuels (Volpe et al., 2016; Valenti et al., 2017a). However, the implementation of a circular model is feasible only if it brings economic, environmental, and social benefits (reducing pressure on the environment, improving the security of the supply of raw materials, boosting economic growth, and creating jobs), pointing out the need for an economic return on investment to provide a suitable motivation to companies (Ghisellini et al., 2016; Chiaraluce, 2021).

When it comes to circular approaches in agri-food, biogas production represents an environmental- friendly strategy to successfully recover large amounts of waste and by-products to produce renewable energy, as it ensures both pollution control and energy recovery (Valenti et al., 2017b; Fagerström et al., 2018; Barros et al., 2020; Mistretta et al., 2022). According to GSE (*Gestore dei Servizi Energetici*), in 2021 there were 2,200 biogas plants producing electricity in Italy, and 80% of them used biomass from the agricultural sector. The anaerobic digestion (AD) consists in a process where the organic matter breaks down naturally in absence of oxygen through biochemical reactions performed by specific bacteria (Mezzadri et al., 2010). The main product of the AD process is biogas, an extremely useful source of renewable energy; an important secondary product is the digestate, a highly valuable biofertilizer that can be used to offset the financial as well as the environmental costs associated with the use of mineral fertilizer (Sagagi et al., 2009). Farms have the potential to implement a regenerative management system through the exploitation of by-products and waste and to produce biogas from biomasses of different origin, mainly slurry and manure from livestock farming, but also olive pomace, slaughter residues, food wastes from the transformation industry (Zarbà et al., 2021). Among the different supply chains, fruit and vegetables accounted for approximately 14% of the total value of the European agricultural production, representing a fundamental sector for many Member States (Rossi, 2019). On the other hand, vegetable wastes are produced in considerable amounts in agricultural activities and transformation processes (Pavi et al., 2017); it is estimated that around 20–22% of fruit and vegetable is loss from post-harvest to distribution (FAO, 2019). The seasonality and geographical localization of vegetable waste set the focus on how to manage them in a sustainable way from a technical, economic and environmental point of view. The valorization of vegetable waste deriving from the transformation process through AD allows to daily manage high quantities of these matrices, guaranteeing the safety of the food chain by moving them away from the factories continuously, even during the moments of mass production. Moreover, anaerobic digestion plants have the logistics, facilities and expertise for storing vegetable waste to be used as feedstock, according to the current best management techniques (Garuti et al., 2021).

Nevertheless, in light of the need of sustainable green biofuels, biogas can be converted into biomethane through a process of purification (consisting of dehydration, desulphurization, removal of ammonia gas, and others) and upgrading (removal of carbon dioxide; Ryckebosch et al., 2011). According to the European Biogas Association, in 2021 Europe had 1,023 biomethane production plants. France, Italy and Denmark are the countries with the highest growth rate of new plants. While Italy counts 27 biomethane plants on its territory, the upgrading of biogas is just started to spread, thanks to the Biomethane Decree of 2018, which boosted the sector. Biomethane is currently considered promising for applications in the transport sector or to be injected in the gas grid, also because Italy is the European leader in terms of natural gas vehicles, representing three quarters of the European fleet (Eyl-Mazzega and Mathieu, 2019). Even if its production generally brings environmental benefits, because the biogas-biomethane chain is considered carbon negative, the conversion process is not always perceived as beneficial, due to the upgrading process costs and energy demand (Molino et al., 2013). However, the biogas-biomethane chain permits the recovery of some resources, such as manure, agricultural waste and agro-industry waste, and OFMSW (Organic Fraction of Municipal Solid Waste), which can be converted into energy (D'Adamo et al., 2019), allowing the implementation of a full circular model (Yazan et al., 2018).

Several studies about the production of biomethane from waste are already available in literature. Browne and Murphy (2013) assessed the production of biomethane from different food waste, showing that food waste has the potential to provide almost 3% of renewable energy for transport. Valenti et al. (2018) exploited the potentiality of the co-digestion of mixtures of by-products and agricultural residues through biomethane potential tests, demonstrating that all the studied feedstock-mixtures could be potentially used for renewable energy generation. Zhu et al. (2019) analyzed the European policy regarding biogas production and utilization to increase biogas/biomethane production. They highlight that a clear strategic vision is required, with multiple policy supports that are constantly being reviewed and revised, evolving to reflect market and regulatory circumstances. Similarly, Murano et al. (2021) analyzed the European and Italian regulations for producing biomethane, underlining the critical issues and opportunities. They also considered three case studies to study the incentive scheme, showing that biomethane is considered a promising opportunity for biogas producers. Throughout a SWOT and PEST analysis, Piechota and Igliński (2021) investigated the biogas-biomethane chain in Poland, identifying in high investment costs, long lead times and a strong energy lobby as the main barriers, and the environmental aspect as the most important advantage. Pappalardo et al. (2022) estimated the potential production of biomethane in Southern Italy, using the Land Use Efficiency index, calculating the environmental sustainability of the biomethane potential of the study area. The authors estimated the number of biomethane plants that could be built, without detracting from the agricultural land area traditionally used to produce food and feed. Furthermore, to overcome uncertainty in the biomethane production and facilitate its implementation to encourage the circular model, it is important to consider the economic profitability of such system. Cucchiella et al. (2015) applied the net present value and discounted payback time for the evaluation of profitability of biomethane plants, in function of the feedstocks used (energy crop, livestock slurries, OFMSW), the plant dimensions and the firm configuration. They found out that profitability is reached only if certain conditions are satisfied, in particular when using by-products in the feedstock. The authors firmly stated that the adoption of incentives is determining to make an investment profitable. The key-role of subsidies is highlighted also in another study by Cucchiella et al. (2019b), performing an economic analysis regarding both biogas and biomethane plants that use several typologies of animal residues. The profitability is reached for 300 kW biomethane plants fed with sheep/goats, by-products and poultry as substrates. Ferella et al. (2019) aimed to determine whether the upgrading of an existing biogas plant could be profitable and in which specific conditions. The considered substrates were maize silage, by-products and OFMSW. According to the results, the upgrading to biomethane never accomplishes profitability, while the profitability can be reached installing new biomethane plants with a capacity of 250 m^3/h using the OFMSW as substrate. Baena-Moreno et al. (2020) evaluated the profitability of the whole biogas-biomethane chain for three different biomethane capacities (50, 100, and 150 m^3/h) in South Spain, using strawberry extrudate as feedstock. The authors found out that the investment in the three scenarios is not economically feasible, and they confirmed the necessity of incentives in order to promote and boost the production of renewable and sustainable energy. Hoo et al. (2020) investigated the role of policy instrument to facilitate upgrading of biogas (produced palm oil mill effluent, food waste, chicken manures and cattle manures) to biomethane in Malaysia, finding that biomethane injection into the grid is economically unsustainable without policy and institutional support. To conclude, Gupta et al. (2022) compared the economic feasibility of four different upgrading technologies to produce biomethane from food waste and cow slurry in the UK. The profitability of a plant is strongly dependent on the upgrading technologies, and adequate carbon taxes should be established to guarantee an economic viability of the biomethane production. Since most of the studies consider OFMSW, by-products and animal slurries as feedstock, as far as the authors know, there are no papers dealing with the economic profitability of the biogas-biomethane chain implemented with vegetable processing waste. To fill this gap, the objective of this paper is to evaluate whether the upgrading of an existing biogas plant, in which the diet includes also vegetable waste from a frozen vegetable plant, could be profitable considering different scenarios. The analysis, conducted through the Discounted Cash Flow (DCF) method, will emphasize if the production of biomethane represents an opportunity for agribusiness entrepreneurs, with the overall aim of reaching a sustainable circular model. The production of green energy from waste and the utilization of the digestate as fertilizer will close the loop of the frozen vegetable processing chain. The reminder of the paper is organized as follows: "Section 2" introduces the policy framework; "Section 3" presents the case study and the economic analysis; "Section 4" shows and discusses the main results. Finally, "Section 5" proposes some remarks and conclusions.

2. Policy framework: From biogas to biomethane

In Italy, the biogas sector expanded significantly in the last decade due to generous government incentives (Benato and Macor, 2019). By contrast, biomethane production has a limited diffusion, substantially derived from the lack of effective subsidies (Banzato et al., 2018). The history of biomethane started in 2011, with the Legislative Decree (LD) 3 March 2011, no. 28, which is considered the reference standard introducing the definition and the urge to incentive its use in transportation. The regime of subsiding was introduced with Ministerial Decree (MD) 5 December 2013. The decree required to use waste and by-products for, at least, 50% of the final weight of the feedstock, and the incentive perceived by the producer was dependent on the final use and guaranteed for 20 years. However, this policy was unsuccessful, and the real start of the sector was reached with the MD 2 March 2018. In line with the provisions of the EU Directives on the promotion of energy from renewable sources, the DM endorses the use of biomethane in the transport sector. The new incentive system was based on the release of CIC (*Certificato di Immissione al Consumo* - Certificate of Emission of Biofuel in Consumption), and the objective of the incentive is to ensure a fair remuneration for the investment and operating costs. There are no limitations concerning the plant size, and the value of subsidies is equal to 375 € for a CIC. One CIC is assigned for 10 Gcal (single counting), and the unitary incentive is equal to 0.305 €/m^3. A premium is recognized for some substrates (as by-products and waste), entitling the producer to receive one CIC per 5 Gcal (double counting). Consequently, the value of the incentive in this case will be equal to 0.61 €/m^3. Furthermore, entrepreneurs who produce biomethane to be used as fuel are entitled to receive of a number of CIC increased by 20%. The incentive system is valid for all new plants that will come into operation by 31 December 2022, for a maximum volume of 1.1 billion Sm^3 biomethane per year. After 10 years, the value of the CIC will change according to market demands. Finally, on 18 December 2018, the new Renewable Energy Directive (RED II) came into force, which obliged the European Member States to request binding proof of sustainability for the generation of electricity and heat from solid and gaseous biomass fuels such as biogas and biomethane, by July 2021 at the latest. In 2021, Italy has issued the LD 8 November 2021 no. 199 which not only implemented the RED II, but also promote a series of interventions to realize the NRRP (National Recovery and Resilience Plan) and encourage the production of renewable energies, like biogas and biomethane. The legislative decree introduces new rules on incentives for the production of biomethane, through the recognition of an equal tariff for both transport and other uses, some clarifications related to feed used in biogas plants that partially convert the production into biomethane, and simplified authorisation procedures referring in particular to infrastructures.

3. Materials and methods

3.1. Case study description

The biogas plant chosen as case study belongs to a frozen vegetable industry located in Central Italy. It is a consortium agricultural company, consisting of 500 farmers operating in Marche, Umbria, Abruzzo and Emilia Romagna, and the total cultivated area is about 6,700 hectares. The cultivation of the raw materials (almost 42,000 t/year) is carried out both under organic (for a 10–15% of the total) and integrated schemes. The company's average production is 35,000 t/year of frozen products, mainly peas, leafy products (spinach, chard, chicory), borlotti beans, French beans, tomatoes and cherry tomatoes, vegetable soup ingredients (celery, Savoy cabbage, leek, pumpkin) and herbs (parsley and basil). The company produces about 6,700 t/year of vegetable wastes (representing 16% of the initial raw material). Table 1 shows the frozen vegetable mass balance for the year 2021.

The main features of the biogas plant are illustrated in Table 2. The electric capacity is of 1 MWe, working for almost 360 days per year. The main substrate is represented by the maize silage, produced by the members of the cooperative, and the diet is generally composed as follows:

- 70% maize silage
- 10% chicken manure
- 20% by-products from the frozen processing (the presence and actual quantity depend on the processing seasons).

For the maximum efficiency of the digestion, the feed should be arranged so as to provide the maximum yield in biogas in the shortest period of time. Energy crops, such as maize silage, present the best productive potentialities, and their presence is essential to guarantee a standardized activity of the plant (Adani and D'Imporzano, 2008; Rath et al., 2013). Since the amount of by-products is scarce, maize silage is implemented as the main component of the digester feed, to standardize the operability of the plant. From the anaerobic digestion, 15,600 t/year of digestate is obtained as secondary product.

3.2. Economic analysis

To understand whether the upgrading of an existing biogas plant could be cost-effective, a profitability analysis, based on the

TABLE 1 Frozen vegetable supply chain mass balance (data from 2021).

	Cultivated surfaces (ha)	Raw material (t/year)	Frozen product (t/year)	Waste (t/year)	Waste (%)
Peas	4,719.80	17,679.76	14,625.99	3,053.77	17
Leafy vegetable	635.10	10,693.23	8,839.41	1,853.82	17
Beans	154.00	654.33	736.25	−81.92*	−13
French beans	439.06	2,853.88	2,498.83	355.05	12
Soup ingredients	157.75	3,725.18	2,789.74	935.44	25
Tomatoes and cherry tomatoes	523.99	4,790.62	4,450.82	339.80	7
Herbs	93.20	1,468.77	1,307.83	160.94	11
TOTAL	6,722.90	41,865.77	35,248.85	6,698.83	

*The borlotti beans' production yield is around 110-115%: for this reason, the waste amount is a negative value.

TABLE 2 Biogas plant characteristics (data from 2021).

Plant capacity (MWe)	1.00
Working time (hours/year)	8,640.00
Biogas (m^3/year)	4,090,975.00
Digester feed (t/year)	20,917.00
Maize silage	15,000.00
Vegetable by-products	3,417.00
Chicken manure	2,500.00
Incentive (€/kWh)	0.280
Digestate (t/year)	15,600.00

DCF method, was performed. The chosen capacity of the final biomethane plant is 250 m^3/h. The definition of the plant size was chosen as a function of the actual biogas plant size. It was not hypothesized an increase of the capacity. The needed data were obtained both experimentally and throughout literature review. The chosen indicators are Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Time (DPBT), and Profitability Index (PI). NPV is the discounted sum of all cash flows, positive and negative, in a certain time horizon; a project is profitable when NPV is positive. DPBT is the time required to recover the invested capital. IRR is the discount rate that makes the net NPV equal to zero. PI represents the ratio between the NPV and the initial investment; a higher PI means that a project will be considered more attractive. Equations (1–4) describe the parameters used to calculate each indicator.

$$NPV = \sum_{t=0}^{n} \frac{I_t - O_t}{(1+r_d)^t} \tag{1}$$

$$\sum_{t=0}^{DPBT} \frac{I_t - O_t}{(1+r_d)^t} = 0 \tag{2}$$

$$\sum_{t=0}^{n} \frac{I_t - O_t}{(1+IRR)^t} = 0 \tag{3}$$

$$PI = \frac{\sum_{t=0}^{n} \frac{I_t - O_t}{(1+r_d)^t}}{C_{inv}} \tag{4}$$

I_t = cash inflows
O_t = cash outflows
r_d = discount rate parameter
n = lifetime of the project (set in 10 years)
t = time
C_{inv} = total initial investment

For the purpose of the study, the following costs were considered:

- Cost of investment (upgrading system, compression, distribution)
- Operative costs (OPEX) for the biogas-biomethane chain
- Diet cost.

3.3. List of assumptions

This work evaluates the profitability of a biomethane upgrading system based on four different scenarios. Starting from the business-as-usual scenario, Case 1, Case 2, and Case 3 were hypothesized to improve the circularity of the system. The four situations are detailed below:

- Business-as-usual scenario: the upgrading is performed on the current biogas plant, without any changes in the basic features.
- Case 1: only 30% of maize silage is used for the digester's diet, to reduce the amount of dedicated energy crop.
- Case 2: only by-products and waste are used for the digester's diet to eliminate the dependance upon the maize silage.
- Case 3: an investment in a distribution point for the biomethane for transportation is included, but 30% of maize silage is kept in the feedstock.

The investment's cost for the biomethane production depends upon the upgrading technology implemented. Starting from the actual biogas plant, we chose pressure swing adsorption technology (PSA) among the different upgrading systems. The advantages of this technology consist in the simplicity of construction, compact and small size, and the possibility of use in small plants (up to 250 Nm^3 of unrefined gas treated per hour; Mezzadri et al., 2010). In Case 3, the distribution plant initial investment was also included, and considered equal to 600.00,00 € (European Commission, 2018).

The OPEX include costs for service, labor, maintenance, energy (if required), and other costs (Stürmer et al., 2016). As the analysis is performed on an existing plant, we do not consider any changes regarding the operative costs of the biogas production, and they remain valid throughout the useful lifetime of the project.

The diet cost is dependent on the maize silage price; for the analysis, in Business-as-usual scenario, Case 1, and Case 3, the purchase cost was 50 €/t. The costs have been increased 2% every year, considering the average fluctuations of the market prices as evidenced from the OECD and FAO forecasts (OECD/FAO, 2021). It was considered a null value for vegetable by-products and chicken manure in all the four hypotheses, but in Case 2 a transportation cost to collect the required waste was considered, and estimated equal to 5.50 €/t.

The profit deriving from the biomethane was calculated based on the incentives provided by the Italian Government. Following the last available decree (MD 2018), to the producer are due the so-called CIC, dispensed by the GSE. As the MD 2018 guarantees the incentive for 10 years, this time span was used in the economic analysis. For the purpose of the study, the value of the CIC will be considered in cubic meters. For the business-as-usual scenario, the CIC is equal to 0.305 €/m^3, as the diet remained chiefly composed of maize silage. In case 1, the CIC is considered with the double counting (0.610 €/m^3) for 70% of the produced biomethane, and with the single counting (0.305 €/m^3) for the resting 30%. In case 2, the CIC is equal to 0.610 €/m^3, as only by-products are used in the digester. Finally, for case 3, the CIC is increased by 20% and equal to 0.366 €/m^3, as the plant produces and distributes biomethane for transportation. In this last case, also the distribution and selling of biomethane is included in the final income of the plant, and the price of biomethane is assumed equal to 0.390 €/m^3 (Consorzio Monviso Agroenergia, 2018). In all the four considered scenario, it was estimated to sell part of the produced digestate as fertilizer.

Table 3 summarizes the main features of each hypothesis.

4. Results and discussion

The profitability of the investment in the upgrading system from biogas to biomethane was assessed in four different scenarios. Table 4 presents the results related to the four indicators (NPV, DPBT, IRR, PI). The analysis indicates that the profitability of the biomethane plants is verified only under certain scenarios.

In the business-as-usual scenario, we took into consideration the investment in the PSA technology without any changes to the basic features of the biogas plant. In this setting, the NPV is negative (-6,748 k€), as well as the PI (-4.67) and the DPBT is >10 years. IRR cannot be calculated in this scenario. These values demonstrate that, at these conditions, the considered timeframe is not sufficient to recover the initial investment and dampen all the costs. The profit made with the produced biomethane and the selling of the digestate is not sufficient to cover the investment, the OPEX and the increasing costs of the feedstock. The current incentive is not adequate to sustain the conversion of a small biogas plant produced especially from energy crops (70%). In fact, with the current policy framework,

TABLE 3 Main characteristics of each hypothetic scenario.

		Business-as-usual scenario	Case 1	Case 2	Case 3
Investment	€	1,445,500.00	1,445,500.00	1,445,500.00	2,045,500.00
Diet cost	€/year	750,000.00	225,0000.00	115,043.50*	225,000.00
CIC	€/Sm^3	0.305	0.305 (30%) 0.610 (70%)	0.610	0.366

*Unitary cost of transportation equal to 5.5 €/t.

TABLE 4 Profitability analysis for the 4 hypothetic cases.

		Business-as-usual scenario	Case 1	Case 2	Case 3
NPV	€	−6,748,603.68	1,509,074.37	4,082,428.71	4,487,217.14
DPBT	Year	>10	3	2	2.5
IRR	%	–	23	48	40
PI		−4.67	1.04	2.82	2.19

European Union aims to limit the share of biofuels originating from food crop-based feedstock, promoting the use of waste and by-products in light of the circular economy approach. This limitation is motivated by concerns about the risk of the so-called indirect land use changes, due to an expanding market of biofuel crops which may lead to displacement from food crop production and the cultivation of new arable land (Börjesson et al., 2015).

To overcome the problematics emerged in the business-as-usual scenario, Case 1 was hypothesized. In this situation, the company decides to rebalance the digester diet by reducing to only 30% the amount of maize silage used. The remaining 70% is composed of by-products and waste. In this second setting, the NPV is positive (1,509 k€), as well as the PI (1.04), and the DPBT is of almost 3 years. The investment becomes profitable starting immediately from year one, as the incentive provided by the GSE is doubled for 70% of the produced biomethane, following the principle of the double counting. Following this approach, the biogas-biomethane chain becomes more sustainable, and the system resembles more to a circular one. However, it is not enough to simply reduce the quantity of maize silage to full the circular principles, as its production still exploit natural resources like land and water, detracting agricultural land to produce food.

To make the process as circular as possible, we hypothesized in Case 2 to remove maize silage from the digester's diet, and use only by-products from the vegetable processing plant and agricultural wastes to produce biogas. The costs for the feedstock are related to the gathering and transportation from the nearby (max. 50 km) companies. Thus, the NPV is positive (4,082 k€), as PI (2.82), and the DPBT is approximately 2 years. The profitability of the plant is connected not only to the absence of cost for the energy crop, but also to the double counting CIC, equal to 0.610 €/m^3, for using 100% of waste substrates, as provided by the MD 2018. The situation improved compared to the previous two scenarios, both for the economic and circular balance, since there are no more constrains related to the use of the energy crop. Nevertheless, if removing the component which standardizes and guarantees a continuous production of biogas, so of biomethane, it is fundamental to rebalance the diet, ensuring a consistent supply of by-products to make the plant working in full regime. In this sense, relationships among agri-business entrepreneurs and the creation of companies' net should be encouraged, favoring the industrial symbiosis where the waste of one becomes the resource of another. In this hypothesis, the cost of the diet is null, in a kind of mutualism/favor where the biomethane producer does not pay the feedstock of the digester, and the "supplier" has no costs related to waste management. It is not unrealistic to consider that, in the future, if this system proved to be profitable, it would also be possible to envisage a remuneration for purchasing the agricultural waste, by paying at an agreed rate or by supplying digestate to farms. It is worth to remember that, with the Legislative Decree 21 March 2022 n. 21, the Italian Government has officially recognized digestate as equivalent to chemical fertilizers. This action contributes to promote circular economy principles, spread ecological practices, and reduce the usage of chemical inputs in agriculture, while increasing the supply of organic matter in soils and limiting the production costs. Furthermore, the Legislative Decree 17/2022 improved the already existing list of agro-industrial by-products employable for the anaerobic digestion, such as coffee silverskins and brewer's grains. The implementation of the usable feed list is a significant step further into making the food industry most circular, allowing to produce more renewable energy and higher quantities of digestate, valorizing a wide spectrum of agri-food by-products, and favoring the industrial symbiosis.

In order to work in perspective of the European objectives outlined in the Green Deal, to reduce net emissions by at least 55% by 2030 and to become the first climate-neutral continent by 2050, the new LD 2021 aims to support the production of advanced biomethane to be used for transport. For this purpose, Case 3 presents an additional investment for the realization of a distribution point for biomethane as transportation fuel. NPV is positive (4.487 k€), PI is positive (2.19), and the DPBT is of 2.5 years, since the CIC is increased of 20% and, in the calculation of the revenue, a sales price to the distributor of 0.39 €/m^3 (1.2 €/kg) was taken into account. Nonetheless, we decided to keep 30% of maize silage into the diet. The whole situation is economically positive, and the payback time reasonable; so, in these terms, it is convenient to invest in the upgrading system of an already existing plant. Following this investment scheme, it is possible to comply with the EU's renewable energy programs, and with the circular economy principles. As for Case 1, circularity is not fully reached as we are still exploiting the energy crop. This minimum amount is maintained to guarantee a standardized and continuous supply of the biofuel to the pump.

In summary, Figure 1 represents the evolution over time of NPV for the four hypothetic scenarios. From the graph, it is evident the inconvenience in investing in the business-as-usual scenario. On the other hand, Case 3 represents the most profitable situation; in fact, even if the initial investment is higher compared to Case 1 and 2 (due to the realization of the distribution point), the production and sale of biomethane as vehicles fuel is able to cover the costs and make viable the plant for the considered period.

Notwithstanding, it is important to make some considerations:

- The decree implementing the RED II for the new incentive schemes has not yet entered into force, so at this time there is no certainty about the duration of the incentive or its amount. However, on the basis of the LD 2021, it will be of the same magnitude for the use of biomethane

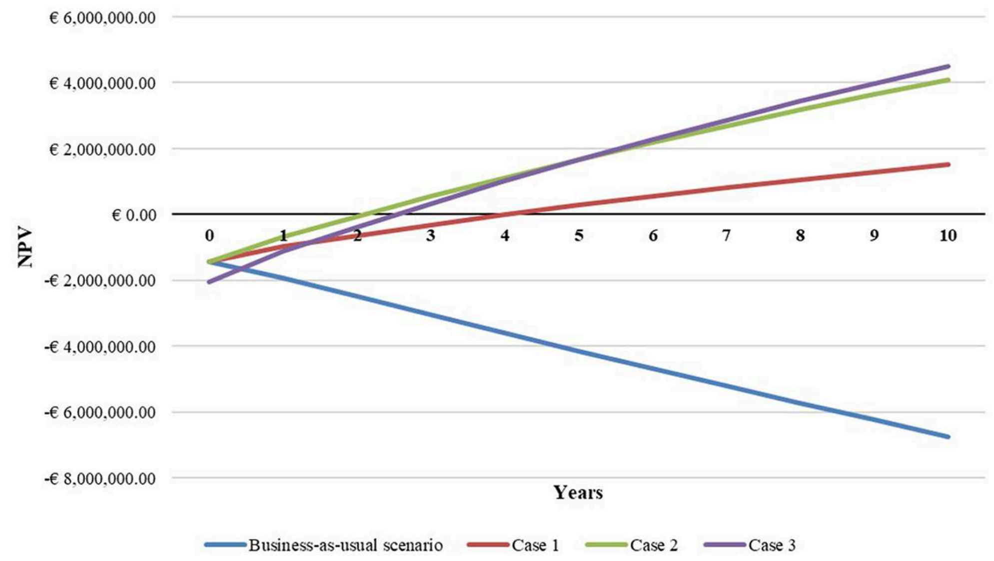


FIGURE 1
NPV values in the 10 years of investment for the four scenarios.

both as vehicles fuel and for other uses. The production of biomethane is strongly dependent upon incentives, that should be calibrated to ensure a fair remuneration to the producers. Baldino et al. (2018) estimated that policy incentives equivalent to 1.50 €/m^3 would be necessary to support a significant amount of renewable methane production using sustainable feedstock.

- The incentive will definitely be linked to the matrices used in the digester, so an optimal balance of the diet is needed to ensure high performances with minimal environmental impact. It is fundamental also to consider the availability of the matrices. Vegetable waste are produced in massive quantities during the specific campaign of each product, and they are not available in the same amount throughout the year. A correct and continuous functioning of the plant requires a standardized diet, both in quality and quantity. To overcome this limit, a winning strategy could be the adoption of cooperative structures, in which more than one producer commits its vegetable by-products to a common plant (like the one taken under consideration in this study) to produce energy. As vegetable waste could not be enough to satisfy the necessities of the digester, the use of other kind of food industry by-products, as well as animal slurries and OFMSW (Cucchiella et al., 2019a), could integrate the diet guarantying a continuous activity of the system. Until now, waste recycling was insufficiently considered in energy system models. To overcome this criticality and encourage the transition to a cleaner renewable energy, collaborative models should be developed to join the energetic system and the production of material, for a more cohesive and interdisciplinary sustainable development (Kullmann et al., 2021).
- The rebalancing of the diet will also be crucial to fully achieve the circular model, which to date is only partially implemented due to the use of energy crops. In this regard, it will be important to define a circular business model to assess the longevity of the project in the long term, and use the produced waste as new production inputs instead of being disposed of in the landfill (Yazan et al., 2018). Nonetheless, the use of waste as input could allow economy of scale. Although circular economy is still at the early stages of development, it provides a reliable framework to radically improve the current business models toward preventive and regenerative eco-industrial development, run by renewable energy directly produced by the waste of the supply chain (Ghisellini et al., 2016).
- With a perspective of sustainable development, and following the dictates of the LD 2021, it will be important to set targets in terms of reduction of GHG (up to 65%, according to the decree). In this regard, biomethane, produced with suitable advanced matrices, can contribute to these results. In addition, the LD 2021 provides that, by 2030, a share of 8% of biomethane will be present in fuel stations.

5. Conclusions

Our study investigates the profitability of upgrading an existing biogas plant to biomethane. The four scenarios highlighted that, if the upgrading is performed maintaining the basic characteristics of the biogas system, the investment is not profitable. This is linked to the high costs of the maize silage, that, from one side, guarantees a continuous activity and production of energy, but, on the other side, does not allow the implementation of a full circular model. Considering this as a starting point, the other three cases propose alternative solutions to cope with the high costs of the investment while give a nod to increase the sustainability and circularity of the production. In all the three hypotheses, the investment is fully recovered and profitable in the considered time span. It is worth to remember that all these arguments are based on the diet costs and not on the incentives, assumed as provided by the current Italian laws. The circular economy model is not completely accomplished as economic feasibility can only be reached in some scenarios with particular conditions. However, as the existing literature suggests, the authors consider it appropriate to rethink the subsidies system, as it is essential to encourage the production of biomethane from waste in order to properly apply the fundamental circular principles, such as the reuse of materials and nutrients, limit the production of waste, produce renewable energy and advanced biofuels.

In general terms, the results show that the cost of running is strongly dependent on the type of upgrading system implemented, which determines the initial investment, and typology of agricultural substrate used in the digester. Moreover, the conversion of the plant is not economically feasible if an adequate subsidy is not provided, as the costs of production are not competitive with the price of natural gas yet. One limitation of the present work is the amount of vegetable waste: the hypotheses were made on the basis that the required amount of vegetable waste is always available. As we know that the quantities of vegetable by-products are limited throughout the year, according to the harvesting and processing period of each crop, the author suggests to implement a cooperative system to collect the agri-food wastes from different companies and farms. In this way, the integration of vegetable waste with animal residues, agricultural scraps and other food processing waste could represent a constant supply of raw material for the digester. Moreover, as many authors suggest, the collection and addition of OFMSW could represent a winning strategy to get rid of a consistent amount of waste while implementing the circular principles to produce renewable energy. Another limitation could be related to the geographical localization of the considered biogas plant. Even if the study is limited on a specific area of Central Italy, findings can be useful to encourage the installation of biogas-biomethane chain plants to favor the ecological transition in Italy, as the produced waste used as feedstock are common for all the vegetable processing plant. In this sense, it would be beneficial to implement the national policy strategy on renewable energy, thus helping to overcome the current energy crisis. Finally, the last limitation is related to the absence of technical specifications regarding the changes in biogas, thus biomethane, according to the different proposed diets. After assessing the profitability of such investment, it could be interesting in the future to test and verify how actually the performance of the plant is affected by the various feedstocks, together with experts in the field. The economic assessment of the upgrading system for biogas to biomethane is an essential element to be provided to the agribusiness entrepreneurs. As they are waiting for the Italian law converting the energy LD, that will establish the incentives and the parameters that will regulate the market, they need all the relevant economic aspects to decide to invest and adopt this solution to establish an innovative circular business model in agriculture. Thanks to the energy production from agri-food waste, the agricultural sector could overcome the current critical situation, limiting the costs, while greening their productive systems.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

GC and DB made the conception and the analysis and interpretation of data. GC drafted the manuscript, tables, and figure. AF revised the work critically and made a contribution in the interpretation of the results. GC, DB, and AF contributed in the acquisition of data and the design of the work. All authors have accepted the final version of the manuscript.

Funding

The present research belongs to an Innovative Doctoral Scholarship with industrial characterization, funded by the Marche Region (Italy) with the resources of the ROP Marche ESF 2014/2020, in favor of the Università Politecnica delle Marche (UNIVPM)—Department of Agricultural, Food and Environmental Sciences (D3A).

Acknowledgments

The authors wish to thank the cooperative Covalm - OrtoVerde for providing data and support to the research.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abokersh, M. H., Norouzi, M., Boer, D., Cabeza, L. F., Casa, G., Prieto, C., et al. (2021). A framework for sustainable evaluation of thermal energy storage in circular economy. *Renewable Ener.* 175, 686–701. doi: 10.1016/j.renene.2021.04.136

Adani, F., and D'Imporzano, G. (2008). *I Fattori Che Rendono Ottimale la Razione Per il Digestore*. Available online at: https://air.unimi.it/bitstream/2434/131906/1/razioni-digestore.pdf (accessed June 30, 2022).

Ambaye, T. G., Vaccari, M., Bonilla-Petriciolet, A., Prasad, S., van Hullebusch, E. D., Rtimi, S., et al. (2021). Emerging technologies for biofuel production: a critical review on recent progress, challenges and perspectives. *J. Environ. Manage.* 290, 112627. doi: 10.1016/j.jenvman.2021.112627

Baena-Moreno, F. M., Malico, I., Rodríguez-Galán, M., Serrano, A., Fermoso, F. G., Navarrete, B., et al. (2020). The importance of governmental incentives for small biomethane plants in South Spain. *Energy* 206, 118158. doi: 10.1016/j.energy.2020.118158

Baldino, C., Pavlenko, N., Searle, S., and Christensen, A. (2018). *The potential for low-carbon renewable methane in heating, power, and transport in the european union.working paper 2017–26. International Council on Clean Transportation* (ICCT). Available online at: https://theicct.org/sites/default/files/publications/Renewable_Gas_EU-28_20181016.pdf (accessed June 21, 2022).

Banzato, D., Canesi, R., and D'Alpaos, C. (2018). Biogas and biomethane technologies: an AHP model to support the policy maker in incentive design in Italy. *Green Energy Technol.* 22, 319–31. doi: 10.1007/978-3-319-75774-2_22

Barbera, E., Menegon, S., Banzato, D., D'Alpaos, C., and Bertucco, A. (2019). From biogas to biomethane: a process simulation-based techno-economic comparison of different upgrading technologies in the Italian context. *Renewable Energy* 135, 663–673. doi: 10.1016/j.renene.2018.12.052

Barros, M. V., Salvador, R., Francisco, D. E., and Piekarski, A. C. (2020). Mapping of research lines on circular economy practices in agriculture: from waste to energy. *Renewable Sust. Energ. Rev.* 131, 109958. doi: 10.1016/j.rser.2020.109958

Benato, A., and Macor, A. (2019). Italian biogas plants: trend, subsidies, cost, biogas composition and engine emissions. *Energies* 12, 979. doi: 10.3390/en12060979

Bentivoglio, D., Finco, A., Bacchi, M. R. P., and Spedicato, G. (2014). European biodiesel market and rapeseed oil: what impact on agricultural food prices. *Int. J. Global Energ. Issues* 37, 220–235. doi: 10.1504/IJGEI.2014.067667

Börjesson, P., Prade, T., Lantz, M., and Björnsson, L. (2015). Energy crop-based biogas as vehicle fuel—the impact of crop selection on energy efficiency and greenhouse gas performance. *Energies* 8, 6033–6058. doi: 10.3390/en8066033

Browne, J. D., and Murphy, J. D. (2013). Assessment of the resource associated with biomethane from food waste. *Applied Energ.* 104, 170–177. doi: 10.1016/j.apenergy.2012.11.017

Chiaraluce, G. (2021). Circular Economy in the agri-food sector: a policy overview. *Ital. Rev. Agric. Econ.* 76, 53–60. doi: 10.36253/rea-13375

Chiaraluce, G., Bentivoglio, D., and Finco, A. (2021). Circular economy for a sustainable agri-food supply chain: a review for current trends and future pathways. *Sustainability* 13, 9294. doi: 10.3390/su13169294

Consorzio Monviso Agroenergia (2018). *Verso il Biometano*. Available online: http://www.monvisoenergia.it/wp-content/uploads/2018/04/SPECIALE_BIOMETANO.pdf (accessed July 15, 2022).

Cucchiella, F., D'Adamo, I., and Gastaldi, M. (2015). Profitability analysis for biomethane: a strategic role in the Italian transport sector. *Int. J. Energ. Econ. Policy* 5, 440–449.

Cucchiella, F., D'Adamo, I., and Gastaldi, M. (2019a). Sustainable Italian cities: the added value of biomethane from organic waste. *Appl. Sci.* 9, 2221. doi: 10.3390/app9112221

Cucchiella, F., D'Adamo, I., and Gastaldi, M. (2019b). An economic analysis of biogas-biomethane chain from animal residues in Italy. *J. Clean. Prod.* 230, 888–897. doi: 10.1016/j.jclepro.2019.05.116

Cusenza, M. A., Cellura, M., Guarino, F., and Longo, S. (2021). Life cycle environmental assessment of energy valorization of the residual agro-food industry. *Energies* 14, 5491. doi: 10.3390/en14175491

D'Adamo, I., Falcone, P. M., and Ferella, F. (2019). A socio-economic analysis of biomethane in the transport sector: the case of Italy. *Waste Manage.* 95, 102–115. doi: 10.1016/j.wasman.2019.06.005

Ellen MacArthur Foundation (2013). *Towards the Circular Economy: Opportunities for the Consumers Goods Sector*. Available online at: www.ellenmacarthurfoundation.org/publications (accessed June 17, 2022).

European Commission (2018). State Aid SA.48424 (2017/N) – Italy - Support scheme for the production and distribution of advanced biomethane and other advanced biofuels for use in the transport sector. Available online at: https://ec.europa.eu/competition/state_aid/cases/269927/269927_1973623_186_2.pdf (accessed July 15, 2022).

Eyl-Mazzega, M. A., and Mathieu, C. (2019). *Biogas and Biomethane in Europe: Lessons from Denmark, Germany and Italy; Etudes de l'Ifri, Ifri: Paris, France*. Available online at: https://www.ifri.org/sites/default/files/atoms/files/mathieu_eyl-mazzega_biomethane_2019.pdf (accessed June 17, 2022).

Fagerström, A., Al Seadi, T., Rasi, S., and Briseid, T. (2018). *The Role of Anaerobic Digestion and Biogas in the Circular Economy*. Cork: IEA Bioenergy.

FAO (2019). *The State of Food and Agriculture 2019. Moving Forward on Food Loss and Waste Reduction*. Rome: FAO.

Ferella, F., Cucchiella, F., D'Adamo, I., and Gallucci, K. (2019). A techno-economic assessment of biogas upgrading in a developed market. *J. Clean. Prod.* 210, 945–957. doi: 10.1016/j.jclepro.2018.11.073

Finco, A. (2012). *Biofuels Economics and Policy: Agricultural and Environmental Sustainability. Biofuels Economics and Policy*. Milano: Franco Angeli.

Garuti, M., Soldano, M., Tonolo, A., and Piccinini, S. (2021). Sottoprodotti vegetali utili a produrre biometano. *L'informatore agrario*. 1, 44–48.

Ghisellini, P., Cialani, C., and Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* 114, 11–32. doi: 10.1016/j.jclepro.2015.09.007

González-Arias, J., Baena-Moreno, F. M., Pastor-Pérez, L., Sebastia-Saez, D., Fernández, L. M. G., Reina, T. R., et al. (2022). Biogas upgrading to biomethane as a local source of renewable energy to power light marine transport: profitability analysis for the county of Cornwall. *Waste Manage.* 137, 81–88. doi: 10.1016/j.wasman.2021.10.037

Gupta, R., Miller, R., Sloan, W., and You, S. (2022). Economic and environmental assessment of organic waste to biomethane conversion. *Bioresource Technol.* 345, 126500. doi: 10.1016/j.biortech.2021.126500

Hoo, P. Y., Hashim, H., and Ho, W. S. (2020). Towards circular economy: Economic feasibility of waste to biomethane injection through proposed feed-in tariff. *J. Clean. Prod.* 270, 122160. doi: 10.1016/j.jclepro.2020.122160

Jain, A., Sarsaiya, S., Awasthi, M. K., Singh, R., Rajput, R., Mishra, U. C., et al. (2022). Bioenergy and bio-products from bio-waste and its associated modern circular economy: current research trends, challenges, and future outlooks. *Fuel* 307, 121859. doi: 10.1016/j.fuel.2021.121859

Khan, M. U., Lee, J. T. E., Bashir, M. A., Dissanayake, P. D., and Ok, Y. S., and Ahring, B. K. (2021). Current status of biogas upgrading for direct biomethane use: a review. *Renew. Sust. Energ. Rev.* 149, 111343. doi: 10.1016/j.rser.2021.111343

Kullmann, F., Markewitz, P., Stolten, D., and Robinius, M. (2021). Combining the worlds of energy systems and material flow analysis: a review. *Energ. Sust. Soc.* 11, 1–22. doi: 10.1186/s13705-021-00289-2

Mezzadri, M., Antonini, E., and Francescato, V. (2010). *Purificazione e Upgrading Del Biogas a Biometano*. Available online at: https://www.venetoagricoltura.org/upload/Bioenergie/Purificazione_upgrading_biogas_in_biometano.pdf (accessed June 20, 2022).

Mistretta, M., Gulotta, T. M., Caputo, P., and Cellura, M. (2022). Bioenergy from anaerobic digestion plants: energy and environmental assessment of a wide sample of Italian plants. *Sci. Total Environ.* 843, 157012. doi: 10.1016/j.scitotenv.2022.157012

Molino, A., Nanna, F., Ding, Y., Bikson, B., and Braccio, G. (2013). Biomethane production by anaerobic digestion of organic waste. *Fuel* 103, 1003–1009. doi: 10.1016/j.fuel.2012.07.070

Murano, R., Maisano, N., Selvaggi, R., Pappalardo, G., and Pecorino, B. (2021). Critical issues and opportunities for producing biomethane in Italy. *Energies* 14, 2431. doi: 10.3390/en14092431

Naquash, A., Qyyum, M. A., Haider, J., Bokhari, A., Lim, H., Lee, M., et al. (2022). State-of-the-art assessment of cryogenic technologies for biogas upgrading: energy, economic, and environmental perspectives. *Ren. Sust. Energ. Rev.* 154, 111826. doi: 10.1016/j.rser.2021.111826

OECD/FAO (2021). *OECD-FAO Agricultural Outlook 2021-2030*. Paris: OECD Publishing.

Pappalardo, G., Selvaggi, R., and Pecorino, B. (2022). Biomethane production potential in Southern Italy: An empirical approach. *Ren. Sust. Energ. Rev.* 158, 112190. doi: 10.1016/j.rser.2022.112190

Pavi, S., Kramer, L. E., Gomes, L. P., and Miranda, L. A. S. (2017). Biogas production from co-digestion of organic fraction of municipal solid waste and fruit and vegetable waste. *Biores. Technol.* 228, 362–367. doi: 10.1016/j.biortech.2017.01.003

Piechota, G., and Igliński, B. (2021). Biomethane in Poland—Current Status, potential, perspective and development. *Energies* 14, 1517. doi: 10.3390/en14061517

Rath, J., Heuwinkel, H., and Herrmann, A. (2013). Specific biogas yield of maize can be predicted by the interaction of four biochemical constituents. *BioEnergy Res.* 6, 939–952. doi: 10.1007/s12155-013-9318-3

Rossi, R. (2019). *The EU Fruit and Vegetable Sector. Main Features, Challenges and Prospects. EPRS. European Parliamentary Research Service, 2019. PE 635, 563*. Available online at: https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/635563/EPRS_BRI(2019)635563_EN.pdf (accessed June 17, 2022).

Ryckebosch, E., Drouillon, M., and Vervaeren, H. (2011). Techniques for transformation of biogas to biomethane. *Biomass Bioenerg.* 35, 1633–1645. doi: 10.1016/j.biombioe.2011.02.033

Sagagi, B., Garba, B., and Usman, N. (2009). Studies on biogas production from fruits and vegetable waste. *J. Pure Appl. Sci.* 2, 115–118. doi: 10.4314/bajopas.v2i1.58513

Stürmer, B., Kirchmeyr, F., Kovacs, K., Hofmann, F., Collins, D., Ingremeau, C., et al. (2016). *Technical-Economic Analysis for Determining the Feasibility Threshold for Tradable Biomethane Certificates-Report*. Brussels: European Renewable Gas Registry, 1–24.

Teixeira, J. A. (2018). Grand challenges in sustainable food processing. *Front. Sust. Food Syst.* 2, 19. doi: 10.3389/fsufs.2018.00019

Valenti, F., Porto, S. M., Cascone, G., and Arcidiacono, C. (2017b). Potential biogas production from agricultural by-products in Sicily. A case study of citrus pulp and olive pomace. *J. Agric. Eng.* 48, 196–202. doi: 10.4081/jae.2017.727

Valenti, F., Porto, S. M., Selvaggi, R., and Pecorino, B. (2018). Evaluation of biomethane potential from by-products and agricultural residues co-digestion in southern Italy. *J. Environ. Manage.* 223, 834–840. doi: 10.1016/j.jenvman.2018.06.098

Valenti, F., Porto, S. M. C., Chinnici, G., Cascone, G., and Arcidiacono, C. (2017a). Assessment of citrus pulp availability for biogas production by using a GIS-based model: the case study of an area in southern Italy. *Chem. Eng. Trans.* 58, 529–534. doi: 10.3303/CET1758089

Vilariño, M. V., Franco, C., and Quarrington, C. (2017). Food loss and waste reduction as an integral part of a circular economy. *Front. Environ. Sci.* 5, 21. doi: 10.3389/fenvs.2017.00021

Volpe, R., Messineo, A., and Millan, M. (2016). Carbon reactivity in biomass thermal breakdown. *Fuel* 183, 139–144. doi: 10.1016/j.fuel.2016.06.044

Yazan, D. M., Cafagna, D., Fraccascia, L., Mes, M., and Pontrandolfo, P., and Zijm, H. (2018). Economic sustainability of biogas production from animal manure: a regional circular economy model. *Manage. Res. Rev.* 41, 605–624. doi: 10.1108/MRR-02-2018-0053

Zarbà, C., Chinnici, G., La Via, G., Bracco, S., Pecorino, B., D'Amico, M., et al. (2021). Regulatory elements on the circular economy: driving into the agri-food system. *Sustainability* 13, 8350. doi: 10.3390/su13158350

Zhu, T., Curtis, J., and Clancy, M. (2019). Promoting agricultural biogas and biomethane production: lessons from cross-country studies. *Ren. Sust. Energ. Rev.* 114, 109332. doi: 10.1016/j.rser.2019.109332

frontiers | Frontiers in Sustainable Food Systems

TYPE Perspective
PUBLISHED 22 December 2022
DOI 10.3389/fsufs.2022.1031900

OPEN ACCESS

EDITED BY
Claudio Bellia,
University of Catania, Italy

REVIEWED BY
Soheila Abachi,
Laval University, Canada
Pooja Nikhanj,
Punjab Agricultural University, India

*CORRESPONDENCE
Raffaella Pergamo
✉ raffaella.pergamo@crea.gov.it

SPECIALTY SECTION
This article was submitted to Social Movements, Institutions and Governance,
a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 30 August 2022
ACCEPTED 07 December 2022
PUBLISHED 22 December 2022

CITATION
Galioto F, Zucaro R and Pergamo R (2022) Environmental challenges and perspectives of the fresh-cuts sector in Italy.
Front. Sustain. Food Syst. 6:1031900.
doi: 10.3389/fsufs.2022.1031900

Environmental challenges and perspectives of the fresh-cuts sector in Italy

Francesco Galioto, Raffaella Zucaro and Raffaella Pergamo*

Consiglio nazionale per la Ricerca in agricoltura e l'analisi dell'Economia Agraria, Rome, Italy

This perspective paper provides insights on the characteristics of the fresh-cut sector in Italy and on the key environmental challenges the sector is currently facing. Specifically, the paper investigates the factors that brought to the development of agro-industrial hubs for fresh-cuts, capable of influencing the income and employment of various local communities in Italy and the factors that contributed causing serious environmental issues, especially related to the disposal of packaging waste and to the consumption and pollution of water resources. Such issues were recently addressed by the EU through dedicated directives and regulations. These regulations require a serious reflection on the strategies to be undertaken for the future of the sector and the surrounding socioeconomic context. The paper concludes with some policy recommendation to overcome existing barriers and, eventually, transform them into opportunities.

KEYWORDS

fresh-cut products, agri-food, sustainable packaging, shelf-life, water resource certificated

Introduction

Fresh-cut fruit and vegetable[1] represents a strategic asset of the Italian agri-food sector, in which private and public sectors have invested and continue to invest heavily for different but synergistic reasons. The private sector, taking advantage of the pedo-climatic vocation and the grounded know-how of some territories, has found in the fresh-cut sector an important leverage that has greatly increased its competitiveness, also attracting important foreign investments (Stranieri and Baldi, 2017). The strong growth on the demand for fresh-cut, linked to the change in lifestyles and consumption of an

1 For fresh cuts it is meant fresh fruit and vegetable, cut, washed and packaged ready for consumption (according with official definitions of fresh-cut products provided in art. 2, Italian law 77/2011, and by the Fresh-cut Produce Association, IFPA). Fresh-cuts include a broad range of products (definition of fresh-cut products - art. 2, Italian law 77/2011), including salads (in single or multi-varieties mixes) in single or multi-dose packs, just cut and washed or slightly processed for the preparation of soups (such as carrots, herbs and spices, chard, celery, corn, radishes, rocket) or fruit in single preparations or fruit salads consumed directly.

ever-increasing share of the population of western countries (Fouayzi et al., 2006; Pilone et al., 2017; Euromonitor, 2021), then stimulated further investments in the sector which favored new entries[2] and the development of related sectors, ranging from firms specialized in the production of precision technologies for agriculture, seeds and packaging (Baldi and Casati, 2009). The spatial proximity of the different stages of the production process, also obliged by the short shelf-life of the product, has led to the development of agro-industrial hubs, capable of affecting the income and employment of various local communities (Capello, 2015). The Italian State, attentive to the needs of the sector and of the surrounding businesses, has intervened by financing projects[3] and by providing subsidies aimed at protecting its territorial assets and stimulating innovation, with special reference to the current challenges the sector is facing, packaging and water uses.

In the following, we will briefly analyze the structural characteristics of the sector to highlight its size and its strategic relevance in some areas to then focus on investigating the current challenges the sector is facing and conclude with some final recommendation to face the existing ones.

Subsections relevant

Structural characteristics of the sector

According to the latest available information, over 700 farms for an area of 6,500 hectares (of which half in greenhouses), i.e., about 3% of overall national area invested in vegetables, are engaged in the production of fruit and vegetables for the fresh-cut sector in Italy (Baldi and Casati, 2009). Over 60% of the fresh-cut production area is located close to the processing industries. Around 70% of the fresh cuts in Italy are salads (30% of which are baby leaf). The reminder 30% consist mainly of spinach, fennel, and melon (Nomisma, 2015). The provinces of Bergamo, Brescia and Salerno hosts the main production hubs, i.e., 35% of the Italian population of farms and 31% of the Italian Utilized Agricultural Area (UAA) involved in the production of fresh-cut. Another 25% of the farms with 30% of the UAA are in the province of Salerno (Southern Italy). The two northern and southern Italian production hubs cooperate to overcome the problems related to seasonality and variety. These aspects contribute in qualifying the Italian fresh-cut sector as a multipolar production system led by few dominant enterprises, which integrate different territorial and production assets, and which can influence the businesses connected to them with their investment choices. The increasing concentration and specialization of the sector allowed to reduce significantly production costs and to acquire growing market shares both in the domestic and in the foreign market, where exports now reach 55–60% of the total product marketed (Quadretti, 2020), triggering further investments and attracting new businesses on the same territory.

Unlike production, the consumption of fresh-cut is particularly widespread in large urban areas from northern and centers Italy (NIELSEN-ISMEA, 2022). Table 1 provides some information about the quantity and value of fresh vegetables and fruit and fresh cuts sold in the market between 2017 and 2021. Worth noting fruit fresh cuts are still a pioneer market niche in Italy since they represent about 0.2% in quantity and 0.4% in value of the total fruit market. Differently, vegetables fresh cuts are about 8% in quantity and 20% in value of the total vegetable market.

From Table 1 appears evident a reduction of the fresh cuts sold in the market in 2020, both in volumes and in values. Some attribute this countertrend to the changing population lifestyle brough about the pandemic (Latella, 2022). This is especially evident for fruit fresh-cuts. However, the market trend started increasing again immediately after the pandemic and it appears to be continuing to grow. Data provided in Table 1 testify the sector's resilience to external shocks because of its ability to mitigate demand contractions by reducing sale prices (the reduction in value recorded between 2019 and 2020 is 3 times higher than the reduction in quantity in the same period).

Current environmental challenges: Packaging and water usage

Fresh-cut, responding to the changing needs of consumption, poses serious environmental problems in part due to the intensive production systems that require highly frequent crop cycles, soil tillage and use of agrochemicals (Morra et al., 2016), in part due to the amount of waste produced at the processing and distribution stage (Plazzotta et al., 2017), in part due to the inappropriate disposal of the packaging (Siracusa and Rosa, 2018) and to the consumption and pollution of the water resources used for washing and disinfecting fruits and vegetables (Ölmez and Kretzschmar, 2009; Lehto et al., 2014)[4]. Added to this is the overarching health problem, increasing risk exposure for consumers (i.e., spread

2 Bonduelle, a French multinational company, began investing in Italy in 2000 and currently controls together with Linea Verde and Consorzio Piana del Sele more than 70% of the fresh-cut market in Italy for salads.

3 Including the PON POFACS project, "Conservabilità, qualità e sicurezza dei prodotti ortofrutticoli ad alto contenuto di servizio" (Preservability, quality and safety of fruit and vegetables with a high service content) founded by the National Operational Program, to which this contribution is due.

4 There are estimates of 1-5 m^3/t of water used for washing and disinfecting fresh-cut. Higher water consumption was estimated for products derived from tuber plants (in particular carrots), lower for salads.

TABLE 1 Quantity and value of various fruits and vegetable processing categories sold in the market: Years 2017–2021.

	Years				
	2017	2018	2019	2020	2021
Fruit					
Quantity (metric tons)					
Fresh	3,015,579	2,919,697	2,917,831	2,927,356	2,912,127
Fresh-cut	2,593	3,378	3,429	3,245	4,934
Value (1.000 €)					
Fresh	5,906,185	5,941,820	5,864,199	6,500,657	6,469,480
Fresh-cut	14,419	19,656	19,526	16,411	25,963
Vegetables					
Quantity (metric tons)					
Fresh	2,347,310	2,327,327	2,259,914	2,470,440	1,714,396
Fresh-cut	108,446	117,890	122,454	121,978	130,474
Value (1.000 €)					
Fresh	4,700,171	4,660,502	4,814,040	5,266,134	3,974,839
Fresh-cut	727,435	774,618	782,595	760,783	813,180

Source: Our elaboration on NIELSEN-ISMEA data (2022).

of salmonellosis intoxication), partly related with the growing habit of consuming fresh-cut products in Europe which oblige industries to identify practicable strategies to extend fresh-cut shelf-life (Ölmez, 2016), sometimes placing environmental problems in the background.

Despite the widespread use of compostable and biodegradable packaging material for fresh-cuts, the problem of packaging usage is still of crucial importance for the sector. Over 40% of the waste disposed of in Europe is related to packaging and only 9% of it is recycled (SPC, 2022). Various solutions are now in place to limit packaging waste, ranging from recycling to the use of biodegradable material derived from agricultural and agri-food waste to the use of edible material. The growing sensitivity of consumers together with regulatory measures put in place by the European Union to limit packaging waste (i.e., the European directive on single-use plastics (SUP) No. 904/2019), triggered an increasing number of businesses to find innovative solutions to reduce the production of packaging waste. Indeed, the EU SUP directive prohibited the use of disposable plastics which include products that are made entirely or partly of plastic and which are typically intended to be used just once or for a short period of time before they are disposed. Biodegradable/bio-based plastics are also considered to be plastic under the SUP directive[5] as well as disposable paper based products with plastic lining.

Some of the main destination of Italian fresh-cut exports, such as France and Spain, have chosen to apply the SUP directive in a very strict way, with the aim of phasing out plastic packaging for fruit and vegetables and promoting the sale of fresh products without packaging. Many retailers in France promoted awareness campaigns to induce costumers to bring their own reusable containers to be filled with clean and washed fruit and vegetables on site. Unlike France and Spain, Italy risks penalties for the delayed and incorrect transposition of the European directive (Napoli, 2022). Indeed, contrary to the SUP directive requirements, the Italian government granted the use of compostable plastic and the use of plastic lining techniques for packaging. Obviously, the easy solution would be of completely eliminating packaging, also in light of the fact that most of the bioplastic used in packaging is not composted (Di Stefano, 2022), at least in Italy. However, this solution would results with unsustainable economic and social (in terms of unemployment) impacts, especially in those regions of the country specialized in the production of fresh-cut. In addition, eliminating the plastic packaging would have the countereffect of increasing environmental impacts, because of the potential increase in food waste due to the reduction in shelf-life of fresh-cut, since this would result in an increase amount of unsold and not consumed fresh-cut products by the expiration date (White and Lockyer, 2020).

5 Biodegradable/bio-based plastics will be considered plastic at least until the SUP directive review scheduled for the 2027, because of the absence of agreed technical standards available to certify that a specific plastic product is properly biodegradable in the marine environment in a short timeframe and without causing harm to the environment.

The problem of water uses adds up to the problem of plastic uses. The food industry ranks third in the consumption of water resources after the chemical and oil industry. Washing fruit and vegetables requires large quantities of water to remove chemical residues (i.e., pesticides). In addition, the water used to clean fruit and vegetables from chemical residues is added with chlorine and other substances to guarantee a minimum shelf-life and to avoid health issues (CFSAN, 2006)[6]. Therefore, the fresh water used to clean and treat fruit and vegetables during processing becomes wastewater. The growing problem of water scarcity makes this issue particularly delicate. In fact, the environmental impact of fresh-cut depends only partially on the methods used to grow fruit and vegetables, i.e., organic/conventional (Paoletti and Raffo, 2022). Most of environmental impacts are confined to the processing stage and are related to the deterioration of the fresh water used to guarantee a long shelf-life and to contain health risks within limits deemed acceptable (Lehto et al., 2014)[7]. Current European legislation allows the reuse of wastewater from industries in agriculture with the overall aim to minimize water consumption[8] (European regulation 2020/741 on the recycling of industrial wastewater, which will be operational in June 2023 at national level). There are relevant studies providing innovative technological solution to treat a reuse agro-industrial wastewater in agriculture capable of minimizing water consumption in fresh-cuts (Ölmez, 2013; Inyinbor et al., 2019; Nahim-Granados et al., 2020). However, the reuse of wastewater in agriculture is currently more theoretical than practical due to different reasons. First, the reuse of wastewater in agriculture implies the creation of *ad-hoc* infrastructures that purifies industrial wastewater and connect it to end users supply points. Urban sewage could be exploited to purify industrial wastewater, where possible[9]. However, it is often necessary to build the required infrastructures from scratch, to allow the reuse of industrial wastewater in agriculture, because of the distance of industrial areas from urban centers. With regard to the fresh-cut agro-industry, the wastewater resulting from the processing of fruit and vegetables is characterized by an high concentration of minerals, whose use in agriculture could lead to soil salinization in the long run, thus, compromising soil' productivity. In addition, the European regulation allows the use of wastewater only from certain types of industries and to irrigate certain types of crops (Annex II, reg EU 2020/741) and some quality specifications prohibit the use of wastewater, even after treatments. Finally, there is a great deal of uncertainty regarding the way in which the European directive on wastewater recycling will be transposed into the operational regulation of Member States.

Policy suggestions to overcome existing challenges

Private (i.e., the development of industrial and retailer private labels) and public voluntary certification schemes (i.e., the designation of origin for the "Piana del Sele" rocket salad) played an important role in promoting fresh cut consumption in Italy (Baldi and Casati, 2009; Latella, 2022). These instruments are still effectively used to build costumers loyalty, maintaining competitiveness and protecting territorial assets (Baldi and Casati, 2009). But this is no longer enough to effectively promote fresh-cuts if not related to the contingent environmental problems above analyzed (Latella, 2022). A good example in the right direction is the private standard of certification "Goccia Verde," recently created by the national reclamation and irrigation association (Associazione Nazionale Bonfica e Irrigazione–ANBI) to certify the sustainable use of water resources carried out by agriculture and agro-industries. The certification requires the observation of strict management, production and processing rules to guarantee the sustainable use of water resources both at ann individual and at a territorial level. To the best of our knowledge, this is the first certification scheme that requires the direct involvement of farmers, industries, and water networks managers.

Voluntary certification schemes could also play a role in promoting the use of edible packaging to limit packaging waste. To date, many solution have been tested for sustainable packaging (Galgano et al., 2015). However, the actual application of these packaging solutions to food is still limited, due to the

6 Chlorine (or other forms of hypochlorous acid) in wash water is still the most common disinfection compound used for fresh-cut, despite the existence of other disinfectants or disinfection methods (i.e., ozone, organic acids, chlorine dioxide, and UV irradiation), because of its efficacious disinfection capability against a wide spectrum of microorganisms and its economic accessibility compared to other disinfectants.The chlorine (Cl_2) added to the fresh water used to reduce microbial contamination and improve produce safety ranges from about 100–700 mg/l and it varies greatly with the quality of the fresh water used for disinfection and with the type of produce treated (Weng et al., 2016).

7 Water quality standards are defined by the water framework directive 96/2000/CE and they include both morphological, biological and chemical alteration, including chlorine and pesticides whose concentration was found to be particularly high in fresh cuts wastewaters.

8 Actually, agro-industries in the fresh-cut sector reuse the washing water to facilitate the removal of chemical residues to minimize the production of wastewater. Nevertheless, the reuse of washing water is limited to avoid the spread of pathogens (Ölmez, 2016).

9 Italy is, actually, under infringements because of failing to comply with the European urban and industrial wastewater treatment regulation in 74 municipalities (regulation n. 91/271/CE). This aspect makes even less feasible the option of exploiting existing wastewater treatment plants to reuse industrial wastewater in agriculture.

high cost of raw materials and the small-scale production. This would, indeed, be a solution to deal with the problem of waste management and of microplastics dispersed in the environment and in water, guaranteeing, at the same time, the maintenance of an appropriate shelf life.

Recent surveys on the field reveal that there is still not a clear evidence that consumers are wishing to accept the use of bio-plastics and edible packaging, mainly because of a perception of a greater health risk (Herrmann et al., 2022). Nevertheless, according with a survey conducted in 2021 by the Osservatorio Packaging del Largo Consumo (Tronca and Secondulfo, 2019), Italian consumers look carefully not only at the product but also at its packaging, and already 14% of consumers do not buy goods that are packed unsustainably.

Although important, voluntary certification schemes are unable to overcome the discussed obstacles on their own. Public campaigns to create awareness among citizens are key element in favoring both the consumption of fruit and vegetables and fresh-cut products. To this end, the Italian government joined the "EU4Health Program" since 2007, which include the free distribution of fruit and vegetables in schools, including fresh-cut products, coupled with food education. This program must be maintained over time as it has contributed promoting greater sensitivity to the consumption of healthy food, as well as sustainable. A final key policy issue is about the need to provide more targeted supports for investments in the packaging sector to further promote the development of solutions capable of increasing fresh-cut shelf-life and their health and environmental sustainability, with particular reference to the techniques used to disinfect unprocessed food and the material used for packaging.

In the opinion of the authors, it is worth continuing to investigate in these directions as this would help contributing finding solutions consistent with regulatory and consumers' attitudes developments and, most importantly, solutions compatible with existing and emerging environmental and socio-economic issues.

These instruments can help make a difference allowing to find sustainable solution to water consumption in agriculture and agro-industry and to limit waste production, but they are still under development and will hardly work if not embedded into a more complex strategic policy framework, including structural policies to bring about the recovery and reuse of wastewater and public support to continue in sustaining/promoting the experimentation of sustainable packaging solutions.

Conclusion

The fresh-cut sector has proven to be resilient in Italy, despite the temporary shocks in volumes sold in the market, related to the change in consumption habits induced by the pandemic, and in values, related to the reduction of the consumers' purchasing power induced by the war in Ukraine accompanied with increasing production costs.

If on the one hand the sector revealed being able to withstands these shocks, on the other the sector is facing important challenges related to the increasing restrictions on packaging and other processing issues involving disinfection techniques and water usage. Finding solutions able to meet consumers and regulators' needs is becoming more and more urgent for both the future of the sector and the social fabric the sector helps to support. Growth perspectives of the sector largely rely on finding a way to tackle these needs. The sector is already reacting in the search for sustainable solutions for both packaging and the re-use of water resources, also by resorting to the development of sustainability brands to raise consumer awareness. But this is a far from simple challenge, also considering the strong influence of the social, health, economic and political framework surrounding the fresh-cut sector. National bodies are working together with agro-industries to identifying and promoting innovative solutions able to offer the appropriate instruments to face existing challenges, turning into an opportunity what is today perceived as a threat. But this is still a game to be played both in terms of regulatory negotiations with the EU and in terms of innovative solutions brought about the technological progress.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RP, FG, and RZ contributed to conception and design of the study. FG wrote the first draft of the manuscript and implemented sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Baldi, L., and Casati, D. (2009). Un distretto della IV gamma? Il comparto che vende tempo libero. *Agriregioneuropa* 5, 1–5.

Capello, R. (2015). *Regional Economics*. London: Routledge.

CFSAN (2006). *Guide to Minimize Microbial Food Safety Hazards of Fresh-Cut Fruits and Vegetables. US.* FOOD and Drug Administration - Center for Food Safety and Applied Nutrition. D.N.: FDA-2008-D-0108. Available online at: https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-guide-minimize-microbial-food-safety-hazards-fresh-cut-fruits-and-vegetables

Di Stefano, D. (2022). *Bioplastica Riciclata Con l'umido? Secondo Greenpeace è Greenwashing Di Stato*. Economiacircolare.Com. Available online at: https://economiacircolare.com/greenpeace-bioplastica-riciclo/ (accessed December 18, 2022).

Euromonitor (2021). *The World Market for Fresh Food*. Available online at: https://www.euromonitor.com/the-world-market-for-fresh-food/report (accessed July 3, 2022).

Fouayzi, H., Caswell, J. A., and Hooker, N. H. (2006). Motivations of fresh-cut produce firms to implement quality management systems. *Appl. Econ. Perspect. Policy* 28, 132–146. doi: 10.1111/j.1467-9353.2006.00277.x

Galgano, F., Condelli, N., Favati, F., Di Bianco, V., Perretti, G., and Caruso, M. C. (2015). Biodegradable packaging and edible coating for fresh-cut fruits and vegetables. *Ital. J. Food Sci.* 27, 1—20. doi: 10.14674/1120-1770/ijfs.v70

Herrmann, C., Sebastian, R., and Sträter, K. F. (2022). Consumers' sustainability-related perception of and willingness-to-pay for food packaging alternatives. *Resour. Conserv. Recycl.* 181, 1–13. doi: 10.1016/j.resconrec.2022.106219

Inyinbor, A. A., Bello, O. S., Oluyori, A. P., Inyinbor, H. E., and Fadiji, A. E. (2019). Wastewater conservation and reuse in quality vegetable cultivation: overview, challenges and future prospects. *Food Control* 98, 489–500. doi: 10.1016/j.foodcont.2018.12.008

Latella, M. (2022). *IV gamma in crisi nella piana del sele, busillo: fatturati in picchiata, vendite a rilento. Corriere Ortofrutticolo*. Available online at: http://www.corriereortofrutticolo.it/2022/06/15/iv-gamma-crisi-nella-piana-del-sele-busillo-fatturati-picchiata-vendite-rilento/ (accessed July 8, 2022).

Lehto, M., Ilkka, S., Laura, A., and Kymäläinen, H. R. (2014). Water consumption and wastewaters in fresh-cut vegetable production. *Agric. Food Sci.* 23, 246–256. doi: 10.23986/afsci.41306

Morra, L., Lahoz, E., Cerrato, D., Pergamo, R., Bilotto, M., Mignoli, E., et al. (2016). New farming protocols for fresh-cut leafy vegetables. *Informatore Agrario*. 72, 35–39.

Nahim-Granados, S., Rivas-Ibáñez, G., Sánchez Pérez, J. A., Oller, I., Malato, S., and Polo-López, M. I. (2020). Fresh-cut wastewater reclamation: techno-economical assessment of solar driven processes at pilot plant scale. *Appli. Catalysis B Environ.* 278, 119334. doi: 10.1016/j.apcatb.2020.119334

Napoli, F. (2022). *Direttiva Sup, l'Italia Rischia La Procedura d'infrazione. Policy Europe*. Available online at: https://www.publicpolicy.it/direttiva-sup-litalia-rischia-la-procedura-dinfrazione-94153.html (accessed July 11, 2022).

NIELSEN-ISMEA (2022). *Statistiche Su Consumo Di Prodotti Ortofrutticoli Di IV Gamma*. Available online at: https://www.ismea.it/istituto-di-servizi-per-il-mercato-agricolo-alimentare (accessed June 4, 2022).

Nomisma (2015). *Rapporto Sulla Competitività Del Settore Ortofrutticolo Nazionale*. Available online at: http://www.unaproa.com/upload/news/2015_03_31_RAPPORTO_ORTOFRUTTA_2015-DEF.pdf (accessed June 15, 2022).

Ölmez, H. (2013). Minimizing water consumption in the fresh-cut processing industry. *Stewart Postharvest Rev*. 9, 1–6. doi: 10.2212/spr.2013.1.5

Ölmez, H. (2016). Chapter 9 - foodborne pathogenic bacteria in fresh-cut vegetables and fruits. *Food Hyg. Toxicol. Ready Eat Foods*. 151–166. doi: 10. 1016/B978-0-12-801916-0.00009-1

Ölmez, H., and Kretzschmar, U (2009). Potential alternative disinfection methods for organic fresh-cut industry for minimizing water consumption and environmental impact. *LWT Food Sci. Technol.* 42, 686–693. doi: 10.1016/j.lwt.2008.08.001

Paoletti, F., and Raffo, A. (2022). Fresh-cut vegetables processing: environmental sustainability and food safety issues in a comprehensive perspective. *Front. Sustain. Food Syst.* 5, 1–16. doi: 10.3389/fsufs.2021.681459

Pilone, V., Stasi, A., and Baselice, A. (2017). Quality preferences and pricing of fresh-cut salads in Italy: new evidence from market data. *Brit. Food J.* 119, 1473–1486. doi: 10.1108/BFJ-09-2016-0419

Plazzotta, S., Manzocco, L., and Nicoli, M. C. (2017). Fruit and vegetable waste management and the challenge of fresh-cut salad. *Trends Food Sci. Technol.* 63, 51–59. doi: 10.1016/j.tifs.2017.02.013

Quadretti, R. (2020). *Quarta Gamma: Export Verso La Normalità*. Available online at: https://www.myfruit.it/import-export/2020/08/quarta-gamma-export-verso-la-normalita.html (accessed May 27, 2022).

Siracusa, V., and Rosa, M. D. (2018). Sustainable packaging. *Sustain. Food Syst. Agric. Indust.* 275–307. doi: 10.1016/B978-0-12-811935-8.00008-1

SPC (2022). *Sustainable Packaging Coalition*. Available online at: https://dashboard.sustainablepackaging.org/events/spc-impact-2022 (accessed June 13, 2022).

Stranieri, S., and Baldi, L. (2017). Shelf life date extension of fresh-cut salad: a consumer perspective. *J. Food Product. Mark.* 23, 939–954. doi: 10.1080/10454446.2017.1266545

Tronca, L., and Secondulfo, D. (2019). *Secondo rapporto dell'Osservatorio sui consumi delle famiglie: Il consolidamento dei nuovi profili di consumo.* FrancoAngeli. p. 1–145.

Weng, S. C., Luo, Y., Li, J., Zhou, B., Jacangelo, J. G., and Schwab, K. J. (2016). Assessment and speciation of chlorine demand in fresh-cut produce wash water. *Food Control* 60, 543–551. doi: 10.1016/j.foodcont.2015.08.031

White, A., and Lockyer, S. (2020). Removing plastic packaging from fresh produce–what's the impact? *Nutr. Bull.* 45, 35–50. doi: 10.1111/nbu.12420

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 22 December 2022
DOI 10.3389/fsufs.2022.1014228

OPEN ACCESS

EDITED BY
Maurizio Cellura,
University of Palermo, Italy

REVIEWED BY
Sergiy Smetana,
German Institute of Food Technologies, Germany
Daniela Spina,
University of Catania, Italy

*CORRESPONDENCE
Anna Irene De Luca
✉ anna.deluca@unirc.it

SPECIALTY SECTION
This article was submitted to Waste Management in Agroecosystems, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 08 August 2022
ACCEPTED 06 December 2022
PUBLISHED 22 December 2022

CITATION
Falcone G, Stillitano T, Iofrida N, Spada E, Bernardi B, Gulisano G and De Luca AI (2022) Life cycle and circularity metrics to measure the sustainability of closed-loop agri-food pathways. *Front. Sustain. Food Syst.* 6:1014228. doi: 10.3389/fsufs.2022.1014228

Life cycle and circularity metrics to measure the sustainability of closed-loop agri-food pathways

Giacomo Falcone, Teodora Stillitano, Nathalie Iofrida, Emanuele Spada, Bruno Bernardi, Giovanni Gulisano and Anna Irene De Luca*

Department of Agriculture (AGRARIA), Mediterranea University of Reggio Calabria, Reggio Calabria, Italy

This work aims to present a methodological proposal based on Life Cycle (LC) methodologies, and circularity performance indicators, to assess closed-loop pathways by providing comprehensive results on economic and environmental impacts generated by agri-food production systems. The methodological approach will be tested on olive oil production systems, one of the most important agri-food chains for Mediterranean countries, whose import and export significance is set to grow in light of the shrinking market supply of seed oils. Some insights for the co-products valorization are provided through the evaluation of the reuse of by-products as a possible resource capable to improve the sustainability of the olive oil farms. The integrated application of three different methodologies, Life Cycle Assessment (LCA), Environmental Life Cycle Costing (ELCC) and Material Circularity Indicator (MCI), enabled comparative evaluation of Extra Virgin Olive Oil (EVOO) production under a linear production model with production under a circular model. The circular scenario was better in most environmental impact categories, registering an improvement in Global Warming Potential (GWP) of nearly 30%. In economic terms, there was a lower production cost for the circular scenario and a lower environmental cost by reducing the use of synthetic products through the reuse of waste products. The circular scenario recorded a higher degree of circularity due to a reduction in virgin raw materials used in the production process and a reduction in non-recoverable waste. The implementation of circular strategies represents one of the possible trajectories to guide the ecological transition, and the proposed methodological framework can support the decisions of both producers and public decision-makers toward more sustainable and efficient production patterns.

KEYWORDS

olive oil sector, circular economy, Life Cycle Assessment, Environmental Life Cycle Costing, investment analysis, Material Circularity Indicator

1. Introduction

The benefits associated with improving resources and adopting Circular Economy (CE) practices are increasingly perceived by companies in any manufacturing sector. Despite this awareness, the adoption of circular practices is still lacking due to the presence of several barriers both technical related to the industrial stage and economic related to investments to initiate such practices (Roos Lindgreen et al., 2022). The current challenge lies with the ability of companies to be simultaneously competitive through continuous improvement of their business and attentive to society's consideration of the cost-benefit ratio related to socio-economic and environmental issues. On the other hand, it is also encountered that not always circular solutions lead to more sustainable outcomes; therefore, it is crucial to assess the sustainability impacts of CE practices before implementing them. To increase knowledge about the efficacy of circular approaches, appropriate measurements of circularity—and its sustainability—in real case studies could be useful to understand entrepreneurs, public policy and decision-makers who are interested in spreading such innovation (Chiaraluce, 2022). Simultaneous assessment of circularity and sustainability is still uncommon in the scientific literature (Stillitano et al., 2021), probably due to a lack of computational approaches and tools which have yet to be validated by scholars.

Since the CE has become the main topic when firms attempt to increase their business by facing resource scarcity and the need to reduce the environmental impacts, several easy-to-apply indicators have been developed over the years, to assess circularity at the micro-level referring only to the production context. Among them, the most widely used indicator is the Material Circularity Indicator (MCI), which focuses its analysis on material flows occurring about a process or product (Ellen MacArthur Foundation, 2015). However, a limitation lies in neglecting the nature of materials in circulation and overall, in not considering the impacts generated by circular strategies, by quantifying environmentally, economically, and socially with convenient measurement units. Therefore, for methodological completion, it is necessary to combine the MCI with other sustainability assessment tools such as Life Cycle (LC) ones (Goddin et al., 2019), i.e., Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA). LC approaches have long been recognized by the scientific community as tools enable to identify the potential hotspots in the life cycle phases of products, allowing to propose of mitigation strategies for more efficient and sustainable management (Ben Abdallah et al., 2022). CE is supposed to help the re-establishment of a new balance between ecological and economic systems, especially within the dynamics of agri-food systems (Cembalo et al., 2020), if the transition into circularity ensures reconciliation of the triple bottom line principles because not all circular practices are sustainable under all circumstances. Respecting circularity may cause environmental externalities, otherwise, it may not guarantee economic viability, making these two concepts not always interchangeable. So, measuring the effects on environmental, economic, and social dimensions is the *sine qua non* for assuring real sustainability based on the principles of the CE (Silvestri et al., 2022). Although the operational tools available to date are not yet at a level of maturity to overcome critical points for their effective integration in the agri-food sector (Stillitano et al., 2021), considerable efforts by the scientific community are being made in terms of methodological advances for circular economy studies (Niero and Kalbar, 2019). To go beyond these limitations, Stillitano et al. (2022) proposed a customized life cycle model with expanded assessment boundaries, including co-products valorization, into a multiple life cycle perspective (cradle-to-cradle), in an attempt to internalize circularity impacts. The model, conceived to be tested on the olive-oil sector, will offer guidance for life cycle scholars and practitioners, and help to legitimate firms' circularity claims.

Regarding LCA, this is one of the most applied metrics to measure the sustainability of CE pathways even if its use always turns out to be limited to evaluating only the environmental aspects of "supposed" circular systems, leaving the assessment of circularity out of the objectives of the study. LCA methodology has emerged over the past 20 years as one of the most effective tools for analyzing environmental issues related to the production of goods and services. The strong global push toward ecological transition has further put the spotlight on this methodology, which is now widely used in eco-design-oriented comparative analyses. Indeed, according to Stillitano et al. (2021), LCA is widely used for the evaluation of circular strategies for assessing the environmental loads of new technologies but also for the evaluation of circularity itself. The agribusiness sector is also a key player in this strong growth of LCA applications, representing a strategic sector for this "green revolution" since the sustainability of humankind depends on it.

In assessing the environmental impacts of new circular strategies, the implementation of the LCA methodology has been interpreted in various ways by scholars. Most research is limited to assessing the environmental impacts generated by the individual process of reuse, recycling, or recovery (e.g., Benalia et al., 2021) of wastes or by-products. This approach also does not allow for an assessment of the effects in terms of circularity, of these strategies, both concerning the product that generated the waste and by-products and the product that will use them once they are valorized (Stillitano et al., 2022). The solution may be to match the product life cycle whose circularity will be assessed with the life cycle whose environmental impacts will be assessed, integrating circular strategies within system boundaries.

Within the international scientific debate on sustainability assessment, Environmental Life Cycle Costing (ELCC) methodology has long attracted great interest. It has been defined as the logical counterpart of LCA analysis for economic evaluation, goes beyond mere cost accounting and is entirely compatible with LCA (Klöpffer and Renner, 2008). This methodology, in addition to the direct monetary flows of the product or service, allows for the estimation of external costs (externalities or environmental impacts), which are the equivalent monetary values of indirect damages that are not explicitly captured in the market (goods or services without a market) (Kerdlap and Cornago, 2021). In the context of a circular economy, the LCC approach can be applied to support the economic decision-making process for products and services. While the main circularity indicators are essentially based on the increase in the utility of resources within an economic model, an approach that assesses the life cycle value flows of a product, process or system is an important complement to both circularity and sustainability assessment. Several academics attempted to use ELCC aligned with LCA to integrate the environmental and economic assessment of closed-loop pathways in the agri-food sector. For example, applicative studies include bale wrap films collection from the agricultural sector (Mayanti and Helo, 2022), food packaging systems (Albuquerque et al., 2019), wastewater management systems to recover nutrients (Estévez et al., 2022). In all the studies analyzed, the most common practice for aligning both tools was to adopt a common database, consider the same functional units and system boundaries, and follow the same methodological steps. Although the use of such a structure does not guarantee synergy as debated by Heijungs et al. (2013), given the lack of standardization for the integration of LCA and LCC, this practice offers the opportunity for closer alignment between these tools (Bradley et al., 2018; Rödger et al., 2018).

In terms of LCA, ELCC, and MCI integration, only three studies have addressed the simultaneous application of these methodologies in the agribusiness sector, which focused on poultry production (Rocchi et al., 2021), urban agriculture (Rufí-Salís et al., 2021), and beer packaging (Niero and Kalbar, 2019).

Starting from these considerations, this work presents a methodological proposal based on LC methodologies, and circularity performance indicators, to assess closed-loop pathways by providing comprehensive results on economic and environmental impacts generated by agri-food production systems. The main objective is to analyze the environmental, economic and circularity performance of applying circular strategies in olive oil systems, by using LCA, ELCC, and MCI approaches. The olive oil sector is one of the main consumers of resources and producers of wastes in both olive cultivation (wood, branches, and leaves) and processing phases (olive pomace, olive mill wastewater, and olive stones). These wastes, if not properly managed, have a high environmental impact and high costs. The adoption of CE strategies throughout the olive-oil supply chain makes wastes amenable to transformation into by-products, allowing them to be valorized as a possible resource that can be converted into a source of income for the farm (e.g., energy, organic matter, irrigation water). To the best of our knowledge, this is the first integrated evaluation using life cycle and circularity metrics for the transition to CE in the olive oil sector. This work attempts to provide some insights into co-products valorization, through the reuse of by-products as a possible resource capable to improve the sustainability of olive oil farms.

2. Materials and methods

2.1. Case study description

Among the Mediterranean countries, Italy represents the third largest producer of olive oil, with 274,000 tons (about 9.1% of world production) and the second consumer, with 479,000 tons (15.3% of consumption worldwide), although the forecast statistics record a decrease in production levels (IOC, 2021). Olive cultivation is mostly confined to southern regions, Apulia, Calabria and Sicily, which overall account for about 70% of the national olive oil production (ISTAT, 2021). Focusing on the Calabria region, in which olive growing plays a significant economic role, particularly in rural contexts (Bernardi et al., 2021), the EVOO production counts for only 24% of total Italian production, because of the considerable qualitative heterogeneity of product, which involves the consequent difficulty in market placement. However, over the last few years, many olive farms are being characterized by the production of high-quality olive oil, due to both the more efficient farming management and the adoption of product and process innovations, to meet the consumer's needs and, therefore, moving toward a market more competitive (Hamam et al., 2022; Zanchini et al., 2022). In terms of circular economy, recently regional olive farms have been moving toward adopting closed-loop strategies mainly based on the valorization of pruning residues, olive oil mill wastewater and olive pomace, transforming them into co-products through techniques that foresee its reuse or recycling.

To analyze the performance of circular strategies with real data, we took over a "circular" olive oil farm (circular scenario) compared to a "linear" olive oil farm (linear scenario) as case studies (Figure 1). Both farms are in Catanzaro's province (Calabria), which maintains the largest share of olive trees spreading, and share the following characteristics: olive-growing area of 100 ha, Olea europea L. *cultivar* Carolea, orchards with 40-year-old trees, planting density of about 200 plants/ha, and a high level of farm mechanization. The olive oil production system in both farms was split into two main subsystems: the olive growing and harvesting phase, and the olive oil extraction phase. Regarding the first phase, in the circular scenario, pruning residues are shredded and buried in the ground, while in the linear scenario, shredded pruning residues are sent to external

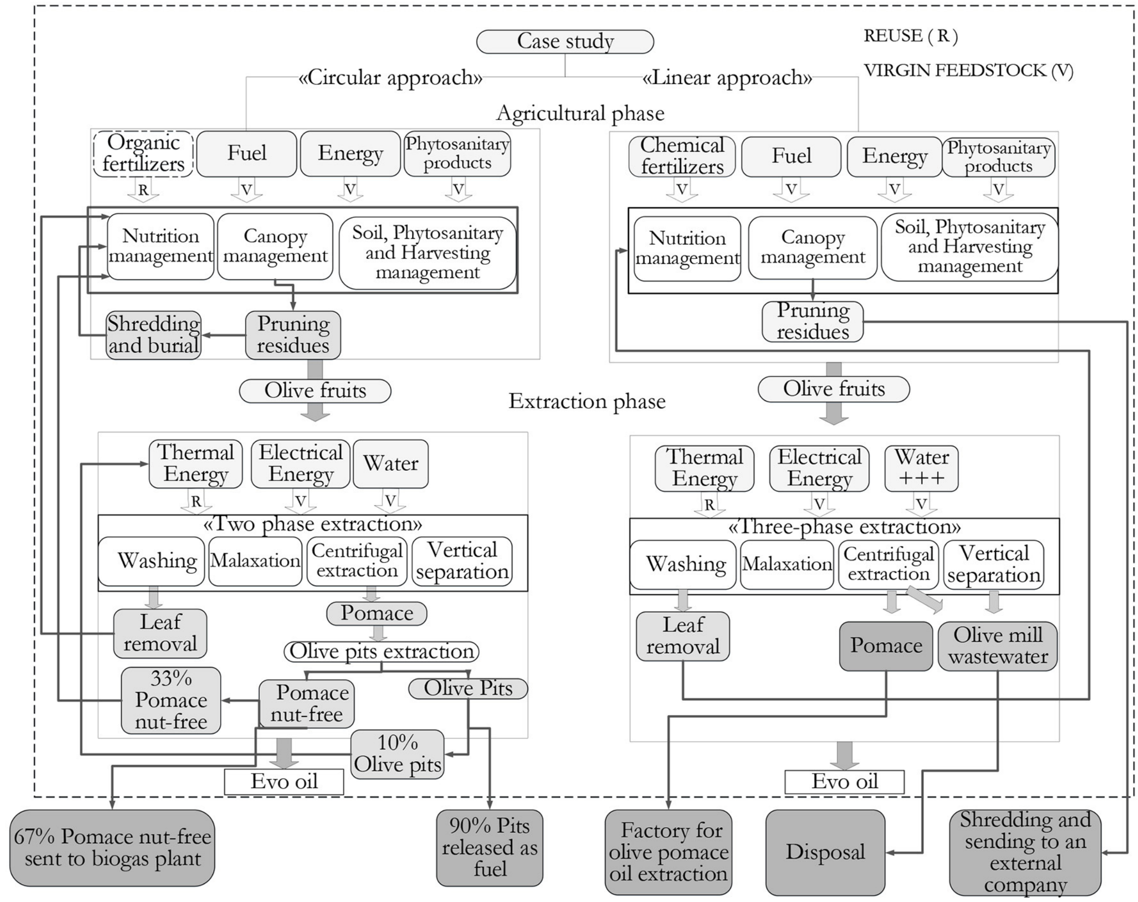


FIGURE 1
Circular and linear scenarios under assessment (Source: Authors' elaboration).

companies as biomass. As for EVO oil extraction, in the circular scenario, olive processing takes place in a continuous olive mill with a total capacity of 10,000 kg per hour. Centrifugal separation takes place in a two-stage decanter, where the paste is not diluted with water. The olive pomace obtained is separated from the olive pits. The latter is partly (10%) reused as thermal energy in the mill. The 33% of pomace nut-free, to which olive leaves are added, is used for organic fertilization of the farm's soils, and the remaining 67% is sent to a biogas plant. In the linear scenario, olive processing takes place in a continuous olive mill with a total capacity of 10,000 kg per hour. Centrifugal separation takes place in a three-phase decanter, where the paste has been diluted with 40% of water. All olive pomace obtained (100%) is sent to the pomace factory for olive pomace oil extraction. The olive pits are not separated from the pomace. Summing up, in the circular scenario, applications concern the pruning residues that are shredded and buried in the soil, the spreading in the field of 1/3 of the stoned two-phase pomace produced during oil extraction, and the use of olive pits extracted from the two-phase pomace to produce the thermal energy needed by the olive mill. In the linear scenario, on the other hand, the pruning residues are given to other farms as biomass, and the pomace obtained from the extraction stage is entirely given to the industrial plant for pomace oil extraction, without separating the olive pits.

2.2. Life Cycle Assessment implementation to the case study

The environmental sustainability assessment was performed using the LCA methodology according to ISO 14040 and 14044 (ISO, 2021a,b). The first step, as described in the aforementioned standards, is to define the goal and scope of the study. The definition of the goal helps to clarify the reasons for carrying out the study, which main elements are to be investigated and to which target audience the study is addressed. Through the contextualization of the study, it is now possible to define the scope in which all the requirements for conducting the life cycle study are defined, such as those relating to the modeling of the production system, the means of obtaining data and the methods for evaluating the results (Hauschild et al., 2018). LCA will be applied to compare two Extra Virgin Olive Oil production systems. In particular, a conventional production system (linear scenario) will be compared with a production system in which circular strategies of reuse, recovery and recycling are introduced (circular scenario). The comparison will aim to verify whether the implementation of these strategies contributes to improving the environmental profiles of EVOO. In order to evaluate the impacts of the two different production techniques on the product, the functional unit will refer to the production of "1 kg of EVOO." The system boundaries under consideration extend "*from cradle to oil mill gate*" and include upstream processes for olives production and core processes for olive oil milling. An economic allocation system was used for the mill products and in particular, by-products of the linear scenario were considered on the basis of the value paid by the pomace factories instead a zero value was attributed to the flows that are managed as waste, while in the circular scenario the percentage to be allocated to olive husk was determined based on its market price while that of pomace was determined on the basis of the surrogate value of the nitrogen component of fertilizers. Given the extensiveness of the biological cycle of the olive tree, it was decided to exclude the planting and early orchard development phases from the environmental analysis since the impact of these phases on the environmental profile of 1 kg of oil would have been negligible. The analyses were therefore limited to the average of four production years (2020/21, 2019/20, 2018/19, 2017/18) at the full maturity stage of the trees (corresponding to the constant production phase), including two years of full production and two years of low yields, in order to consider the alternating bearing phenomenon. The second step of the LCA is the compilation of the Life Cycle Inventory (Table 1).

The processing data are "primary data" collected directly from the study companies through a specific questionnaire. In particular were collected: data on the duration of tillage operation, fuel consumption, maintenance and typology of machinery involved; data on quantity, typology, number of fertilizers and phytosanitary compounds, and the related periods of application; data on yield of olives and wood from pruning. Regarding the data on oil mill unitary processes, were collected the following elements: the energy consumption of the crusher measured using the tools of the Fluke 179 True RMS digital multimeter; the data on water consumption were measured using a flowmeter and the data on the fuel used for heating were measured using the flowmeter installed in the system. Through the methodology described by Zampori and Pant (2019), atmospheric emissions of N_2O, NO_X, NH_3, and NO_3 emissions in water were estimated. P emissions to water were estimated using SALCA-P emission models (Prasuhn, 2006). Emissions to soil, air and water were calculated according to the assumptions reported by Zampori and Pant (2019). Emissions from fuel combustion were estimated according to Nemecek and Kägi (2007). Secondary data on background processes were obtained from Ecoinvent 3.7 (Weidema et al., 2013).

All the steps described so far were also shared with the life cycle cost analysis, the inventory of which, however, was realized by monetizing the material and energy flows of the environmental inventory (see Table 1).

The environmental inventory data were processed using SimaPro 9.2 software (Goedkoop et al., 2013). Life Cycle Impact Assessment was carried out by the Re.Ci.Pe 2016 Midpoint Impact Assessment method (Huijbregts et al., 2017) through 18 impact categories.

2.3. Environmental Life Cycle Costing implementation to the case study

The economic analysis was carried out through the ELCC methodology, aligned with LCA to evaluate the internal and external costs of the scenarios under study. To align ELCC with LCA a common database was adopted, considering the same functional unit and system boundaries, and following the same methodological steps.

The internal costs include all costs incurred throughout the life cycle of each scenario. For the purpose of this analysis, the whole life cycle of the agricultural phase (60 years) per scenario was divided into six main stages: (1) planting stage (*year 0*), (2) unproductive stage (*1st-4th year*), (3) increasing production stage (*5th-15th year*), (4) constant production stage (*16th-56th year*), (5) decreasing production stage (*57th-60th year*), (6) end-of-life stage (*60th year*). All costs were organized into plantation costs, where the design cost (i.e., soil chemical analysis, choice of cultivar, and design of planting distance) and initial investment cost (i.e., the quota on land improvements, the purchasing of plant propagation material, the rental cost of machinery for holes diggings and tree grubbing up) were taken into account; operating costs during the production stages and linked to agricultural operations; and-end-of life costs, i.e., disposal costs arising from the plant removal. Concerning the olive oil extraction phase, the full life cycle (20 years) was split into three stages: (1) start-up stage, (2) operational stage, and (3) end-of-life stage. Within the start-up stage, design and initial investment costs for the extraction component were considered. The costs related to the operational stage included all operating costs of the olive oil extraction. At the end-of-life stage, the disposal cost resulting from the removal of the extraction plant was estimated as the residual value of the machinery and calculated at 50% of the cost of construction. Particularly, operating costs were split into variable (material and energy costs, human labor cost, interests on advance capital) and fixed costs (ownership costs of investments in machinery and land, i.e., depreciation, insurance, repairs and maintenance, interests on capital goods,

TABLE 1 Simplified environmental and economic life cycle inventory.

Process	Input	Unit	Circular scenario	€kg^{-1}	Linear scenario	€kg^{-1}
Fertilization	Organic fertilizer (N 11%)	kg	0.735	0.294	//	–
	N 11%, P2O5 22%, K2O 16%	kg	//	–	0.441	0.265
	Organic leaf fertilizer (N 9%)	kg	0.007	0.017	0.004	0.011
	Self-produced wet pomace	kg	1.250	–	//	–
	Leaves and twigs	kg	0.221	–	0.221	–
	Boric acid 11%	kg	0.002	0.018	0.002	0.018
Pest control	Cupric oxide 75%	kg	0.003	0.033	//	–
	Kaolin	kg	0.029	0.088	//	–
	Soy lecithin	kg	0.000	0.004	//	–
	Bacillus thuringiensis Berliner var. Kurstaki	kg	0.000	0.007	//	–
	Spinosad	kg	0.002	0.055	//	–
	Copper oxiclorid 37.5%	kg	//	–	0.004	0.031
	Fosmet (200 g/l)	kg	//	–	0.002	0.028
	SPADA 200 EC					
	Acetamiprid 200	kg	//	–	0.001	0.074
Technical operations	Diesel fuel for tillage	kg	0.018	0.015	0.018	0.015
	Diesel fuel for shredding pruning residues	kg	0.007	0.005	–	–
	Diesel fuel for spreading leaves and twigs	kg	0.005	0.004	0.005	0.004
	Diesel oil for pomace spreading	kg	0.005	0.004	–	–
	Diesel fuel for fertilization	kg	0.007	0.005	0.007	0.005
	Diesel fuel for pest control	kg	0.024	0.019	0.023	0.019
	Diesel fuel for harvest shaker	kg	0.013	0.011	0.013	0.010
	Diesel fuel for pre-harvest rolling	kg	0.039	0.032	0.039	0.031
	Gasoline for chainsaw and brush cutter	kg	0.005	0.004	0.005	0.004
	Oil	kg	0.004	0.039	0.004	0.039
	Grease	kg	0.003	0.011	0.003	0.010
Work	Tillage	h	0.002	0.064	0.002	0.064
	Shredding pruning residues	h	0.003	0.027		
	Spreading leaves and twigs	h	0.003	0.043	0.002	0.032
	Pomace spreading	h	0.002	0.032		
	Fertilization	h	0.001	0.011	0.001	0.021
	Pest-control	h	0.001	0.064	0.001	0.064
	Pruning	h	0.012	0.263	0.012	0.260
	Arrangement of pruning residue for the chipper machine	h	0.011	0.143	0.010	0.142
	Transportation and handling	h	0.007	0.045	0.007	0.044

(Continued)

TABLE 1 (Continued)

Process	Input	Unit	Circular scenario	€kg^{-1}	Linear scenario	€kg^{-1}
	Rolling pre-harvest	h	0.002	0.013	0.002	0.013
	Cleaning borders with brush cutter	h	0.003	0.045	0.003	0.044
	Harvest shaker	h	0.010	0.080	0.010	0.079
	Moving nets for harvesting	h	0.010	0.336	0.010	0.332
Agricultural products	Olives	kg	6.250	–	6.250	–
	Wood	kg	0.368	–	0.368	–
Oil milling	Electricity for moving olives	kWh	0.003	0.001	0.003	0.001
	Electricity for washing	kWh	0.021	0.007	0.011	0.004
	Electricity for milling	kWh	0.024	0.008	0.028	0.009
	Electricity for malaxing	kWh	0.006	0.002	0.008	0.003
	Electricity for horizontal separator	kWh	0.123	0.040	0.125	0.040
	Electricity for oil centrifugation	kWh	0.023	0.007	0.034	0.011
	Electricity for pit separator	kWh	0.028	0.009	–	
	Water	m3	0.002	0.003	0.003	0.006
	Heat	MJ	0.392	–	0.392	0.059
Work	Milling, moving and cleaning	h	0.002	0.027	0.002	0.027
	Surveillance	h	0.003	0.022	0.003	0.022
Industrial products	EVOO	kg	1.000		1.000	
	Pomace	kg	6.156		3.094	
	Husk	kg	0.750		//	
	Wastewater	l	//		4.519	

rental shed, taxes, and administration overheads) for each life cycle stage.

The external costs concern the monetization of externalities by assigning a specific value to the environmental impacts of a product. To date, the main path for calculating externalities and integrating LCA-LCC is to monetize environmental impacts resulting from LCA studies, struggling to translate environmental impacts into economic impacts. Thus, starting from the LCA results obtained here, the Environmental Prices approach (de Bruyn et al., 2018), which expresses the WTP for less environmental pollution in Euros per kilogram of pollutant, is applied through the SimaPro software to evaluate external costs. Operatively, a monetary weight is given to each environmental indicator by applying the corresponding external cost factor. The environmental indicator referred to the reference unit selected for the LCA under study; the external cost factors accounted for different environmental impacts were taken from Environmental Prices Handbook. The environmental prices identified provide average values for the EU28, for emissions from an average emission source at an average emission site in the year 2015 and are distinguished according to the environmental categories assessed (de Bruyn et al., 2018; Durão et al., 2019).

Subsequently, preparatory to the investment analysis, the total revenues for the entire life cycle of each scenario were calculated by multiplying the product yields (olive and EVO oil) by their market price, which referred to the last harvest season, i.e. 2021/2022, including EU Agricultural Policy subsidies. Table 2 shows the main assumptions made in the study.

2.4. Investment analysis

As a final step, an investment analysis was carried out by calculating specific indicators, i.e., Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Gross Margin (DGM), and Payback Period (PBP). These represent the most common indicators used to compare investment options, which are based on the cash flow model (Stillitano et al., 2019; Ben Abdallah et al., 2022).

TABLE 2 Main technical and economic parameters adopted in the study for both scenarios.

Agricultural phase	
Life cycle (years)	60
Olive yield (t ha^{-1})	9.6
Olive price (€ kg^{-1})	0.50
Daily wage workers (€)	51.00
Life cycle (years)	20
Oil yield (%)	16
EVO oil price (€ kg^{-1}) (ISMEA, 2022)	4.00
Daily wage workers	51.00

The NPV and IRR indicators were calculated according to **Equations (1)** and **(2)**, respectively, as suggested by Moreno et al. (2017):

$$NPV = \frac{\sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - I_0}{\sum_{t=1}^{n} TP} \quad (1)$$

where, t is the time of the cash flow (year); n is the investment lifetime; CF is the net cash flow in the t-th year; r is the discount rate; I_0 is the initial investment; and TP is the total oil production. NPV indicator value has been defined for the FU of 1 kg of EVO oil.

$$\sum_{t=1}^{n} \frac{CF_t}{(1+IRR)^t} - I_0 = 0 \quad (2)$$

where IRR is the discount rate, which will make the NPV equal to zero.

When the conditions NPV > 0 and IRR > r occur, the investment is profitable; otherwise, it should be rejected.

The formula for calculating the PBP indicator is presented in **Equation (3)**, as proposed by Tse et al. (2016):

$$BP = LNC\frac{ADC}{DCA} \quad (3)$$

where, LNC is the last period with a negative discount cumulative cash flow; ADC is the absolute value of discount cumulative cash flow at the end of the period LNC; DCA is the discount cash flow during the period after LNC. The payback period, defined as the expected number of years required to recover the initial investment, is often used as an indicator of a project's riskiness (Mastoras et al., 2022). In any case, the payback period must be shorter than the time horizon considered.

The DGM indicator provides information on project profitability as advised by Stillitano et al. (2019) defined in **Equation (4)**:

$$DGM = \frac{\sum_{t=1}^{n} \frac{TR_t}{(1+r)^t} - \frac{VC_t}{(1+r)^t}}{\sum_{t=1}^{n} TP} \quad (4)$$

where TR_t is the total revenue in the t-th year; VC_t is the variable cost in the t-th year; t is the time of the cash flow (year); n is the investment lifetime; r is the discount rate and TP is the total oil production. DGM indicator value has been defined for the FU of 1 kg of EVO oil.

To perform the profitability analysis of the scenarios under study all of the costs and revenues were discounted for the entire life cycle of 60 years (olive grove lifetime) and 20 years (oil mill lifetime), for the agricultural phase and extraction phase, respectively. To select a discount rate, the opportunity cost approach in terms of alternative investments with similar risks and times was used (De Luca et al., 2018). Here, a discount rate set to 2 and 5% was assumed for the agricultural phase and extraction phase, respectively. During the life cycle, constant prices by excluding adjustments for inflation were taken into account (Hussain et al., 2005).

2.5. Material Circularity Indicator implementation to the case study

The circularity assessment was performed by calculating the Material Circularity Indicator (MCI), which measures how much linear flow has been minimized and remedial flow maximized for its components and, at the same time, for how long and intensively (Rocchi et al., 2021). The MCI has a range of values from 0 (100% linear) to 1 (100% circular). According to the Ellen MacArthur Foundation (2015) and Goddin et al. (2019), the formula for calculating the MCI of a product is as follows (**Equation 5**):

$$MCIp = 1 - LFI * F\ (X) \quad (5)$$

where LFI represents the Linear Flow Index, i.e., the percentage of material flow originating from virgin sources and ending up as non-recoverable waste, while F(X) represents the utility-constructed factor of the linear component of material flows.

LFI is computed by dividing the amount of material flowing in a linear chain by the sum of the amounts of material flowing in a linear and a restorative chain. The index takes a value between 1 and 0, where 1 is a completely linear flow and 0 is a completely restorative flow. The index is derived by **Equation (6)**:

$$LFI = \frac{V + W_0}{2M} \quad (6)$$

where, V is the mass of virgin raw material used in manufacturing; W_0 is the mass of non-recoverable waste attributed to the product, while M is the mass of the finished product. V and W_0 are computed by the **Equations (7)** and **(8)**, respectively:

$$V = M(1 - F_R - F_U - F_S) \quad (7)$$

$$W_0 = M(1 - C_R - C_U - C_C - C_E) \quad (8)$$

where F_R represents the recycled fraction of the feedstock, F_U the fraction from reused sources, and F_S the fraction of the biological materials used which originate from sustained production; while C_R represent the fraction of the product collected for recycling at the end of its use phase, C_U the fraction of the product going into component reuse, C_C the mass of the product comprising uncontaminated biological materials that are composted, and C_E the mass of the product comprising biological materials from sustained production used for energy recovery.

Finally, F(X) is defined in the **Equation (9)**:

$$F(X) = \frac{0.9}{X} \quad (9)$$

where the utility X considers the length and intensity of the product's use phase. The length component (L/L_{av}) accounts for any reduction (or increase) in the waste stream in a given amount of time for products that have a longer (or shorter) lifetime (L) than the industry average (L_{av}). The intensity of use component (U/U_{av}) reflects the extent to which a product is used to its full capacity, relating the average number of functional units achieved during the use of a product (U) and the average number of functional units achieved during the use of an industry-average product of similar type (U_{av}). These two components are combined as follows:

$$X = \frac{L}{L_{av}} \cdot \frac{U}{U_{av}} \quad (10)$$

For assessing the circularity degree, inputs and outputs have been defined for each scenario. In the circular scenario, among the inputs, we find pruning residues, part of the biphasic pomace, and leaves and olive pits that are "reused components" in the production process; organic fertilizer from "recycled" sources; as well as pesticides, water, fuels, and energy from virgin raw materials. Among the outputs, we find the residual part of pomace and olive pits as "recoverable waste" for energy valorization. In the linear scenario, the inputs such as fertilizers, pesticides, water, fuels, and energy are all derived from virgin raw materials, while the outputs include the pruning residues as "recoverable waste" for "energy valorization," the pomace and vegetation water that represent a waste "recoverable for other uses."

Finally, to assess the uncertainty of MCI results, the variance of the data collected for the four production years (2020/21, 2019/20, 2018/19, 2017/18) was evaluated and then, the value of the MCI within the range of variance was calculated.

Furthermore, to integrate life cycle-based and circularity indicators and jointly evaluate the environmental and economic performance of the two scenarios also in the light of the increase or decrease of the circularity level measured by MCI, the marginal variation of the circular scenario compared to the linear scenario was assessed relying on the following equation (**Equation 11**):

$$MVI_{i,j} = \frac{\Delta I_{i,j}}{\Delta MCI_j} = \frac{\left(\frac{I_{i,1} - I_{i,2}}{I_{i,1}}\right) \times 100}{MCI_2 - MCI_1} \quad (11)$$

where, $MVI_{i,j}$ represents the value of Marginal Variation of the *i-th* Impact indicator for the *j-th* scenario (1=linear/2=circular); $\Delta I_{i,j}$ is the percentage deviation between the *i-th* Impact indicator for the *j-th* scenario; ΔMCI_j represents the difference between the values of MCI for the *j-th* scenario.

Considering the environmental and economic impacts and the level of circularity of the linear scenario as baseline, the positive and negative deviations for the specific indicators was accounted and compared to the positive or negative deviation of the MCI.

3. Results

3.1. LCA results

The impact assessment using the Re.Ci.Pe method shows an advantage in almost all impact categories for the circular scenario (Table 3). The improvement of performance ranges from a reduction of 4% in "Fine Particulate Matter Formation" impact category to a reduction of 75.56% in the "Freshwater eutrophication" category. On average, therefore, there is an improvement of about 40% in all impact categories except for "Stratospheric ozone depletion," "Terrestrial acidification," and "Marine eutrophication," categories where the circular scenario shows higher impacts. For the first of these three impact categories, the worsening is caused by field emissions and, in particular, dinitrogen monoxide emissions caused by the distribution of more nitrogen fertilizers. The same causes are also to be found for the other two impact categories, where the largest contributors are, for the "Terrestrial Acidification" category, the highest ammonia and nitrogen monoxide emissions and, for the "Marine Eutrophication" category, the highest nitrate emissions.

The contribution analysis of impacts (Figure 2) also confirms that fertilization is the first hotspot related to nitrogen distribution. Indeed, the circular scenario uses almost double the amount of nitrogen and this results in higher emissions of N_2O, NO_x, NH_3, and NO_3, especially for "Stratospheric ozone depletion" (98.09%), and "Fine particulate matter formation" (95.87%). In the linear scenario, the impacts related to synthetic fertilizer production are more significant for "Ionizing radiation" (65.77%) and "Mineral Resources

TABLE 3 Characterization of impacts related to 1 kg of EVOO.

Impact category	Unit	"Circular approach"	"Linear approach"	Circular/Linear
Global warming	kg CO2 eq	1.24E+00	1.76E+00	−29.57%
Stratospheric ozone depletion	kg CFC11 eq	1.86E-05	1.30E-05	+43.38%
Ionizing radiation	kBq Co-60 eq	2.59E-02	7.29E-02	−64.51%
Ozone formation, Human health	kg NOx eq	1.53E-02	1.66E-02	−7.61%
Fine particulate matter formation	kg PM2.5 eq	1.77E-02	1.84E-02	−4.00%
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.54E-02	1.67E-02	−7.68%
Terrestrial acidification	kg SO2 eq	2.46E-02	2.20E-02	+11.73%
Freshwater eutrophication	kg P eq	2.86E-04	1.17E-03	−75.56%
Marine eutrophication	kg N eq	6.70E-03	5.08E-03	+31.69%
Terrestrial ecotoxicity	kg 1,4-DCB	1.93E+00	5.87E+00	−67.04%
Freshwater ecotoxicity	kg 1,4-DCB	1.19E-01	1.94E-01	−38.56%
Marine ecotoxicity	kg 1,4-DCB	1.49E-01	2.22E-01	−32.72%
Human carcinogenic toxicity	kg 1,4-DCB	4.58E-02	9.59E-02	−52.29%
Human non-carcinogenic toxicity	kg 1,4-DCB	2.48E+00	3.46E+00	−28.42%
Land use	m2a crop eq	3.18E-02	6.34E-02	−49.81%
Mineral resource scarcity	kg Cu eq	6.94E-03	2.03E-02	−65.72%
Fossil resource scarcity	kg oil eq	2.36E-01	4.59E-01	−48.70%
Water consumption	m3	2.42E-02	3.75E-02	−35.54%

Source: Authors' elaboration.

Scarcity" (66.20%). For both scenarios, the second hotspot is the production of pesticides, which affects mainly the following categories: "Marine ecotoxicity," and "Freshwater ecotoxicity." For the "Water consumption" category, the major contribution is due to the milling phase, especially for the circular scenario. Wastewater disposal only affects the linear scenario using a three-stage extraction system and causes a significant impact in the Freshwater eutrophication (36.38%) and Marine eutrophication (16.66%) categories. It should be noted that wastewater treatment generates a positive impact in terms of treated water available for the ecosystem.

3.2. ELCC results

Table 4 shows the main results of the economic assessment referred to the internal costs of the agricultural phase. In line with the proposed methodology, all costs were quantified for each life cycle stage of the olive scenarios. In terms of investment cost in the planting stage, the worst performance is reached by the circular scenario, equal to 7,555.40 *vs.* …7,495.40 €ha^{-1} year^{-1} attained by the linear one. This is due to the higher costs for the purchase of both the pomace spreading and shredding machines. In contrast, as we move into the other stages of the life cycle, the circular scenario achieves the best performance, although a general increase in costs is found in both scenarios because of the more complex management of olive groves linked to harvesting and pruning operations that are carried out from these stages.

Focusing on the constant production stage, the best results achieved by the circular scenario, with a value of 4,332.28 *vs.* …4,454.09 €ha^{-1} year^{-1} reached by the linear one, are mainly due to lower fertilizer purchase, because of the reuse of the co-products such as pruning residues, olive pomace and olive pits that return to the production cycle as an input. Specifically, olive pits return to the oil mill for producing thermal energy.

The olive oil production costs incurred during the extraction phase for the two scenarios examined are shown in Table 5, highlighting the variable and fixed costs per kg of product obtained. The extraction cost is higher in the circular scenario, with a value of 0.41 *vs.* …0.39 €kg^{-1} reached in the linear scenario, with an increase of 5.13%.

This is mainly due to the higher start-up investment costs incurred for the purchase of an olive pit separator, used to extract olive pits from the two-phase pomace to produce the thermal energy required by the olive mill. These costs translate into the highest fixed costs (0.28 *vs.* …0.27 €kg^{-1}) for the quota of the machinery and land investment ownership (i.e. depreciation, insurance, repairs, and maintenance). Concerning variable costs, the highest incidence reached by the circular scenario is due to

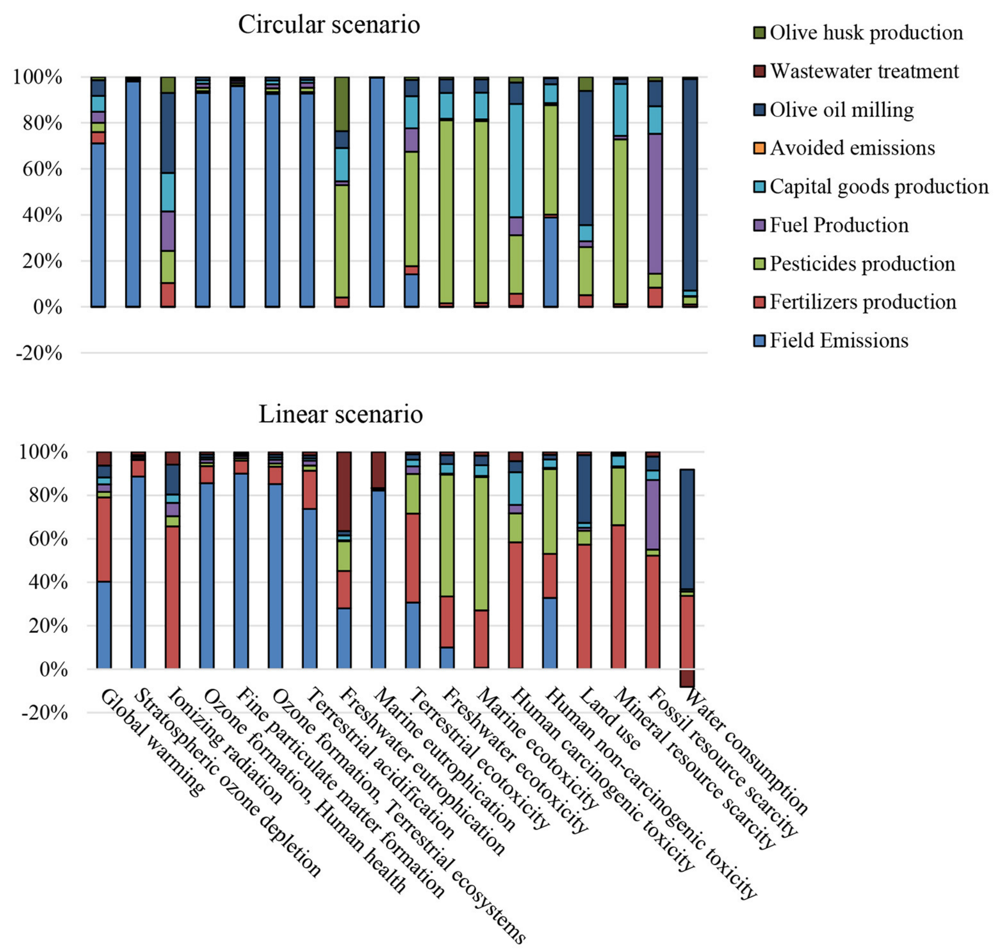


FIGURE 2
Contribution analysis of EVO oil production (Source: Authors' elaboration).

the higher input cost (0.066 *vs.* ...0.062 €kg^{-1}), and human labor cost (0.065 *vs.* ... 0.053 €kg^{-1}) due to the increased use of manpower to manage the operations associated with the production of olive pits.

By adding the olive production cost and the operating cost of olive oil extraction, the total production cost of EVO oil for both scenarios was obtained, as shown in Figure 3. The cost of olive production was estimated by dividing the operating cost incurred in the constant production stage by the olive yield and then multiplying the value thus obtained by the amount of olives needed to obtain one kilogram of oil. The olive production cost was lower for the circular scenario with a value of 1.87 €kg^{-1} than that achieved in the linear scenario of 1.94 €kg^{-1}, with a reduction of 3.62%. The final results showed the best performance reached by the circular system with an EVO oil production cost of 2.28 *vs.* ... 2.33 €kg^{-1} obtained from the linear one (−2.16%).

The results of the evaluation of external costs per scenario are reported in Figure 4. In line with LCA results, the environmental cost contribution analysis revealed that the olive production phase is the most impactful compared to the extraction phase in both scenarios. However, the circular scenario showed the best results with a deviation of 3.71% compared to the linear scenario. The impact categories producing the greatest externalities were particulate matter formation with 64.83% of the total (*vs.* ...64.77% of the linear scenario) and terrestrial acidification (17.5 *vs.* 14.0%). The climate change category achieved the lowest environmental costs in the circular scenario (5.96 *vs.* 8.04) due to lower emissions for fertilizer production.

3.3. Investment analysis results

The findings of the investment feasibility analysis revealed that, in the EVO oil production phase, the circular system was the most economically feasible alternative, presenting an NPV equal to 0.91 €kg^{-1} (*vs.* 0.59 €kg^{-1} of the linear one) and an

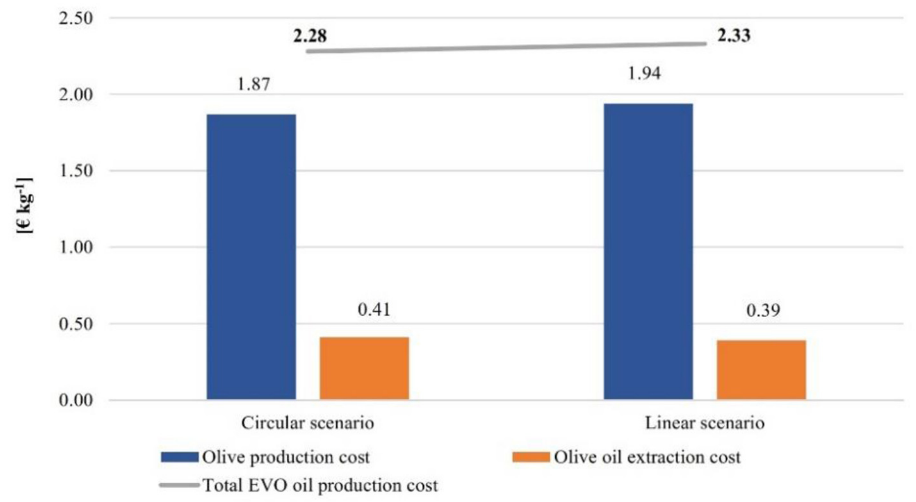


FIGURE 3
Total costs of EVO oil production per scenario (Source: Authors' elaboration).

TABLE 4 Olive production costs of the circular *vs.* linear scenario per life cycle stages (€ ha^{-1} $year^{-1}$).

Life cycle stages	Circular scenario	Linear scenario
Planting stage (year 0)	7,555.40	7,495.40
Unproductive stage (1^{st}-4^{th} year)	2,102.17	2,326.95
Increasing production stage (5^{th}-15^{th} year)	3,887.61	3,972.05
Constant production stage (16^{th}-56^{th} year)	4,332.28	4,454.09
- Tillage (input cost + human labor cost)	231.07	214.80
- Fertilization (")	779.43	827.97
- Disease control (")	314.90	306.40
- Pruning (")	617.60	633.60
- Harvesting (")	680.00	748.00
Decreasing production stage (57^{th}-60^{th} year)	4,418.96	4,298.67
End of life stage (60^{th} year)	10,986.67	11,164.86

Source: Authors' elaboration.

TABLE 5 Olive oil extraction costs of the circular *vs.* linear scenario (€kg^{-1}).

Item cost	Circular scenario	Linear scenario
Start-up investment costs	0.16	0.15
Total operating (extraction) costs, of which:	0.41	0.39
Total variable costs	0.13	0.12
Input cost	0.066	0.062
Human labor cost	0.065	0.053
Interests on advance capital	0.004	0.003
Total fixed costs	0.28	0.27
Machinery and land investment ownership costs	0.081	0.079
Rental shed	0.064	0.064
Interests on capital goods	0.027	0.026
Taxes	0.047	0.047
Administration overheads	0.059	0.058
End-of-life costs	0.081	0.073

Source: Authors' elaboration.

IRR of 40.30% (*vs.* 40.10%) (Table 6). Furthermore, according to the oil mill lifetime of 20 years, the proposed scenario had a payback period of 2.58 years (*vs.* 2.71 years), indicating a full recovery of the initial investment.

Finally, also in terms of the DGM indicator, which amounts to 2.98 €kg^{-1} (*vs.* 2.22 €kg^{-1}), the circular scenario was the most profitable and economically feasible alternative. The higher profitability of the circular system was positively affected by the lower input costs incurred in the agricultural phase and the increased revenue from the additional sale of olive pits, which reaches a selling price of 0.15 €kg^{-1} and are used for household heating.

It should be noted that the profitability of both scenarios has been positively affected by including European subsidies. A sensitivity analysis carried out by excluding public subsidies revealed adverse results for both systems, proving that olive grove management is not sustainable and economically viable. This suggests that olive growing in many Mediterranean countries is still heavily dependent on public intervention.

3.4. MCI results

The MCI results show that the best performance is effectively achieved by the circular scenario with a value of 0.68 out of 1, unlike the linear scenario in which the MCI reaches a value of 0.53 out of 1 (Table 7). This better result is due to both a lower quantity of virgin raw materials (V), because of the reuse of the co-products obtained in both agricultural and extraction phases, and lower production of unrecoverable waste (W). Owing to the lack of studies applying MCI to the olive oil system, it is difficult to contextualize its score. The only applications of the MCI to the agricultural system concerned tomato production in the study by Rufí-Salís et al. (2021), with an MCI value of 0.46 out of 1, and the poultry sector in Rocchi et al. (2021), with a value of 0.48 out of 1.

The uncertainty analysis, carried out through the evaluation of data variance collected for the four production years (2020/21, 2019/20, 2018/19, 2017/18), showed a low uncertainty degree of MCI results (cfr. Table 7). The same analysis proves the significance of the results, as a low standard deviation of V and W values is found from the four production years. A difference of 15% emerges between the two scenarios; in particular, the virgin material flows are significantly lower in the circular scenario (about 22% compared to the linear scenario) as are those of the non-recoverable waste (<50% compared to the linear scenario).

4. Discussion

4.1. Environmental implications

The introduction of circular strategies in agriculture undoubtedly represents a crucial challenge in the pathways of ecological transition. In a global scenario with a world population of eight billion and projections suggesting that it will reach almost 10 billion by 2050 (United Nations, 2022), it is clear that food production will play an increasingly central role. To avoid exceeding the carrying capacity, it will be of growing importance to reduce the consumption of virgin resources, valorizing waste products that would otherwise have to be managed as waste, further burdening the system. The challenge is to grow by reducing resource exploitation, waste and environmental burdens.

The application of the LCA methodology has made it possible to show how much and in which manner the environmental profile of a product is changed for the better or the worse by adopting circular strategies. The subsequent application of the Material Circularity Indicator made it possible to assess the degree of circularity of the innovative scenario compared to the linear one, but without giving any indication of the environmental impacts. It is clear that in the assessment of circular strategies it is not enough to assess only the degree of circularity, just as it is not enough to assess only the environmental impacts: an integrated assessment of the two environmental aspects is required, adding also the assessment of the economic and social aspects. Starting from these assumptions, it is important to first check the robustness of the results. By comparing the environmental profile of the linear scenario with some EPD-certified oils, it was possible to observe substantial comparability for the impact categories in common between the EPD method and the Re.Ci.Pe. method (Global warming, Terrestrial acidification, Freshwater eutrophication). Considering that one liter of oil is equivalent to 916 gms, simply multiply our results by 0.916 to scale the values to the same Functional Unit used in EPD certifications (1 l of EVOO). It should also be considered that only upstream and core process impacts should be calculated, excluding bottling impacts. In terms of "Global Warming," the linear scenario has an impact of 1.61 kg CO_2 eq, which is comparable with both "Monini Gran Fruttato" oil (EPD, 2022) which has an impact of 1.88 kg CO_2 eq and De Cecco oil (EPD, 2017) which has an impact of 1.41 kg CO_2 eq.

The impact category "Terrestrial acidification" is the second category that can be compared between the different environmental analyses and has a value of 0.0202 kg SO_2 eq for the linear scenario of the present study, 0.0253 kg SO_2 eq for "Monini Gran Fruttato" oil (EPD, 2022) and 0.012 kg SO_2 eq for "De Cecco" oil (EPD, 2017). The last category "Freshwater eutrophication" has a value of 0.0011 kg P eq for the linear scenario of this study, 0.0653 kg P eq for "Monini Gran Fruttato" oil (EPD, 2022), and 0.006 kg P eq for "De Cecco" oil (EPD, 2017).

These results are also consistent with the literature review carried out by Guarino et al. (2019) who analyzed the impacts in terms of "Global Warming" in 18 different studies, using one liter of olive oil as a reference unit.

Having verified the robustness of the results of the linear scenario, a critical comparison can be made with the circular scenario. As can be seen from the inventory analysis, the circular strategies allowed the replacement of part of the synthetic fertilizers with crop residues and by-products from the mill. This provided a double benefit related to the reduction of impacts but also the reduction of waste. If we had expanded the boundaries of the system by considering disposal-related impacts, the results

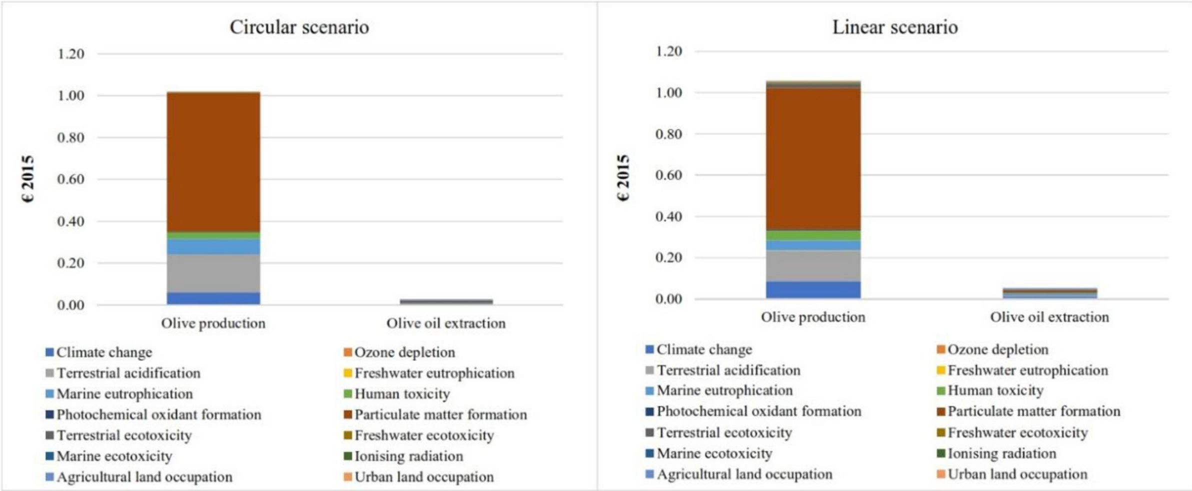


FIGURE 4
Environmental cost contribution analysis (Source: Authors' elaboration).

TABLE 6 Investment analysis of the circular *vs*. linear scenario.

Economic indicator	Unit	EVO oil production phase	
		Circular scenario	Linear scenario
Net Present Value (NPV)	€kg^{-1}	0.91	0.59
Internal Rate of Return (IRR)	%	40.30	40.10
Payback Period (PBP)	years	2.58	2.71
Discounted Gross Margin (DGM)	€kg^{-1}	2.98	2.22

would probably have been even more strongly in favor of the circular scenario.

As was also discussed during the analysis of the results, the adoption of circular strategies does not always bring only benefits, so their adoption must necessarily be evaluated through a life-cycle analysis in order to assess possible burden shifting. An expansion in the adoption of circular strategies could bring further significant benefits. For example, pomace could first be used for biogas production (Benalia et al., 2021) and digestate eventually used as fertilizer. Value could still be extracted from a product that is conventionally considered waste.

4.2. Economic and circularity implications

In addition to the environmental issues, several concerns can affect the economic performance of adopting circular strategies in olive oil systems. As discussed by Ncube et al. (2022), the difficulties to start closing the loop in the olive oil production sector appear to be economical and organizational, which, if overcome, become cost-effective paths.

As our study showed, circular techniques necessarily require greater investment in machinery and technology. In the circular scenario examined, more machines are required, i.e., shredding machines for pruning residues, pomace spreading and olive pit extractor, whose use allows the reuse of by-products as input and thus the reduction of chemical fertilizers and thermal energy from virgin raw material. Shredded pruning residues likewise offer an opportunity to improve soil functioning as tangible water and soil conservation measure, also reducing erosion and preserving soil moisture. This agricultural operation allows to reduce the appearance of weeds and thus the application of herbicides, as well as contributes to the improvement in fertility and C sequestration (Gómez-Muñoz et al., 2016; Taguas et al., 2021). The other application that takes part in the reduction of chemical fertilizer use is the spreading of two-stage pomace from olive oil extraction. The use of pomace is also finding increasing application as a soil conditioner and fertilizer due to the decreasing extraction of pomace oil in specific industries. Similar conclusions were reached by the study of Foti et al. (2022), who assert the current use in agriculture of olive pomace as a soil conditioner and fertilizer, as well as in bioenergy production and for the extraction of polyphenols intended

TABLE 7 MCI results.

Scenario	Production years	V	W	LFI	MCI
		(kg)	(kg)	(0/1 scale)	(0/1 scale)
Circular	2020/21	1.02	3.60	0.28	0.72
	2019/20	1.07	4.22	0.34	0.66
	2018/19	1.07	4.62	0.34	0.66
	2017/18	1.05	3.98	0.32	0.68
	AV	1.05	4.11	0.32	0.68
	Mdn	1.06	4.10	0.33	0.67
	Min	1.02	3.60	0.28	0.66
	Max	1.07	4.62	0.34	0.72
	SD	0.0262	0.4281	0.0288	0.0288
	σ^2	0.0007	0.1832	0.0008	0.0008
Linear	2020/21	4.45	8.58	0.46	0.53
	2019/20	4.95	9.34	0.47	0.53
	2018/19	4.48	8.89	0.47	0.53
	2017/18	4.48	8.64	0.47	0.54
	AV	4.59	8.86	0.47	0.53
	Mdn	4.48	8.77	0.47	0.53
	Min	4.45	8.58	0.46	0.53
	Max	4.95	9.34	0.47	0.54
	SD	0.2421	0.3446	0.0047	0.0038
	σ^2	0.0586	0.1187	0.0000	0.0000

V, Virgin feedstock; W, Waste unrecoverable; LFI, Linear Flow Index; MCI, Material Circularity Indicator; AV, Average Value; Mdn, Median; SD, Standard Deviation; σ^2, Variance.
Source: Authors' elaboration.

for pharmaceutical, food, or cosmetic industries. Until a few decades ago, however, pomace oil extraction carried out with solvents was flourishing and the sale of pomace to processors was profitable. Because of the emergent apprehensions from the public about the use of organic solvents in food processing (Ncube et al., 2022), pomace has fully lost its economic value and it is ordinary for it to be taken for free by pomace factories.

Olive pit extraction is also considered a circular practice due to its use for thermal energy production (Stempfle et al., 2021). Considering that cold olive oil extraction does not require water at high temperatures, the use of olive pits in the mill is limited. Therefore to a large extent, it is sold as fuel for households, going to be a good source of biomass and income for the enterprise. As argued by Hermoso-Orzáez et al. (2020), olive pits with a high calorific power by thermochemical conversion could be converted into different forms of energy also contributing to the mitigation of global warming.

In addition to high investments in innovative material recovery and extraction techniques, the valorization of the oil by-products is hindered by bureaucratic and authorization challenges, as well as difficulties in planning for the supply and seasonal availability of the raw material (Ncube et al., 2022).

Financial support from the public sector could help companies in the initial investment of by-product valorization technologies, enabling them to overcome some of the barriers to adopting circular strategies.

In terms of material flow restoration at farm level, our research results showed better performance for the circular scenario with an MCI value of 0.68 out of 1 *vs.* the linear scenario reaching a value of 0.53. This means that in the circular scenario there is both a lower use of virgin raw material and a lower production of unrecoverable waste. In the former case, the use of virgin resources is replaced by the reuse of the co-products obtained both in the agricultural phase, i.e., pruning residues that are shredded and buried in the soil, and in the extractive phase, where part of the nut-free pomace along with the leaves are used in the organic fertilization of farm soils, and the olive pits to produce the thermal energy needed by the olive mill. The circular system is also characterized by less waste that cannot be recovered (unrecoverable waste) or can be recovered for

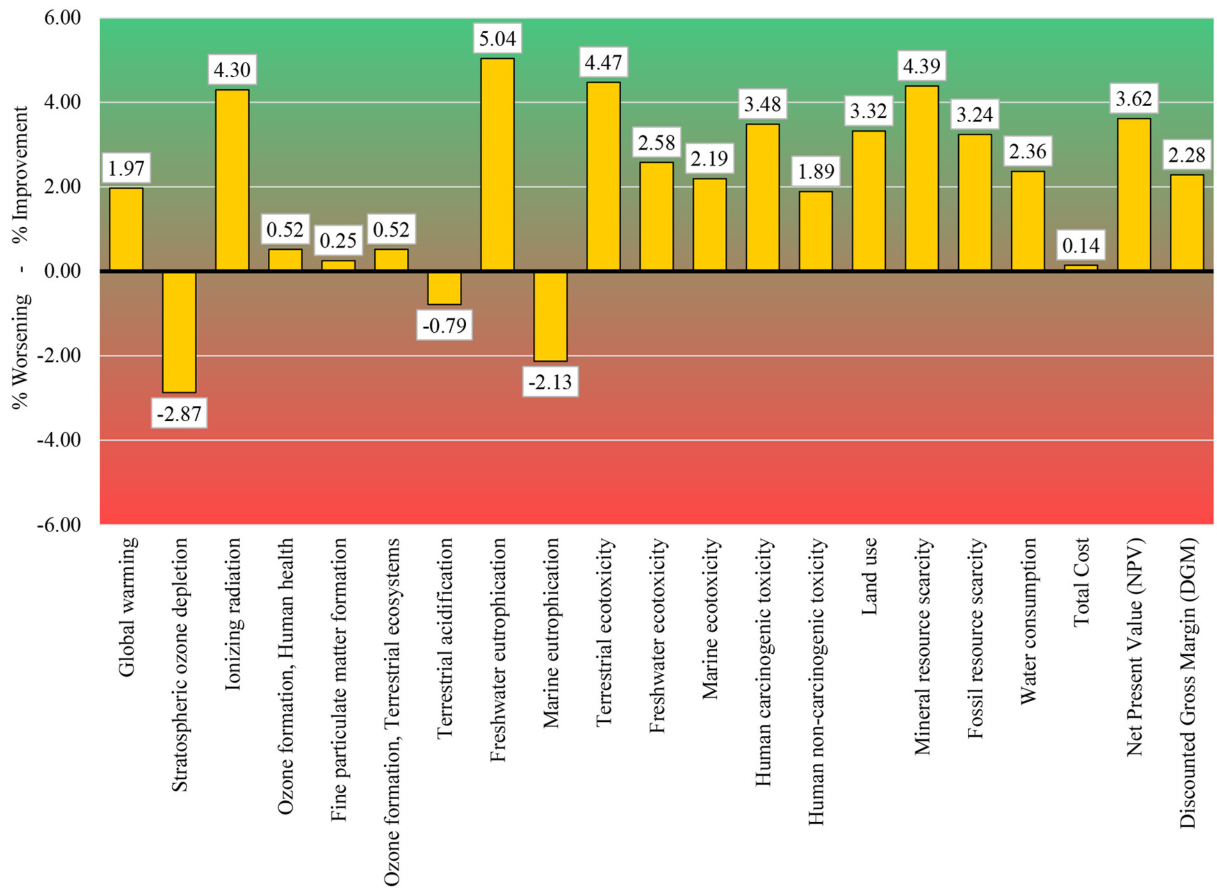


FIGURE 5
Marginal percentage variation, from the linear scenario (baseline), for each LCA and LCC indicator (Source: Authors' elaboration).

other uses. Specifically, pomace and pruning residues are not counted in the circular scenario waste. In addition, emissions from LCA results that are lower in the circular scenario were taken into account among the non-recoverable waste. The greater degree of circularity achieved through the application of closed-loop pathways on the olive farm under study represents a means of making environmental improvements and increasing resource productivity.

4.3. Trade-off between LC indicators and MCI

The marginal variations of each environmental and economic impact indicators were assessed by relating the percentage change of circular scenario to the linear scenario (baseline), as already mentioned in Section Material Circularity Indicator implementation to the case study. The results presented in Figure 5 show, therefore, the percentage deviation (positive or negative) of impacts per indicator as circularity increases by one percentage point. Any increase >1% indicates an improvement in environmental and/or economic impacts more than proportional to the increase in circularity, any increase <1% indicates an improvement less than proportional to the increase in circularity, any decrease indicates a worsening of the environmental and/or economic impacts relative to the increase in circularity.

For almost all scenarios it is observed more than proportional increases, which demonstrates the effectiveness of the circularity strategy in terms of environmental and economic sustainability. For specific environmental indicators like "Ozone formation—Human health," "Fine particulate matter formation," and "Ozone formation—Terrestrial ecosystems" the improvement is less than proportional to the increase in circularity, as well as is the case for "Total Cost." For the three environmental indicators, the causes are to be found in the by-product valorization process, while in the case of the economic indicator, the cause is the increase in investment costs for the circular scenario against a reduction in the costs associated with the purchase of production factors. As regards "Stratospheric ozone depletion," "Terrestrial acidification," and "Marine eutrophication," as already discussed in the discussion of the results of the LCA analysis, the worsening is largely due to the increase in field emissions. In particular for "Stratospheric ozone depletion" and "Marine eutrophication," this worsening is more than proportional to the increase in circularity, so it deserves special attention in terms of eco-design to limit this burdens shifting.

5. Conclusions

This study aims to assess the sustainability performance of circular strategies in the EVO oil production system, applying environmental, economic, and circular metrics at the micro-level. It is well-known that olive oil production causes significant environmental impacts and economic concerns due to the production of several by-products that are difficult to manage. The implementation of closed-loop pathways allow reusing, recycling, or enhancing such by-products, moving toward more sustainable and efficient production patterns. Indeed, using specific technologies, by-products can be managed as a possible resource that can be converted into a source of income for the farm (e.g., energy, organic matter, irrigation water). However, the transition to a circular and sustainable model remains a complex challenge needing an approach that includes not only supply chain actors but also public decision makers. In addition, there is a need to overcome the various obstacles, both technical related to the industrial phase and economic related to investments to initiate circular practices. Despite being particularly anthropized, the olive oil supply chain lends itself well to circular modeling, which is instead inherent in natural ecosystems.

The methodological proposal here shown, based on LC methodologies (LCA and ELCC) and circularity indicators (MCI), provides comprehensive results on environmental and economic impacts, and circularity performance of applying closed-loop strategies in olive oil systems. In scientific literature, the integrated applications of LC approaches and circular economy metrics refer to single process components (e.g., agricultural phase, mill wastewater, and olive pomace) rather than to the overall production process. Through the proposed LC model, it was possible to evaluate the sustainability performance of circular strategies along the entire olive oil supply chain.

In terms of environmental assessment, due to not counting energy and transport in the MCI implementation the use of LCA methodology becomes essential for the return of a reliable result and in particular to verify whether the adoption of circular techniques contributes effectively to the mitigation of environmental impact categories and does not instead to burden shifting. For example, the circular scenario was found to allow a double benefit related to the reduction of impacts and wastes, with the replacement of part of the synthetic fertilizers with crop residues and by-products from the olive-oil mill.

From an economic point of view, our study shows how the circular scenario requires greater business investment when closed-loop strategies are implemented. The purchase of machines for separating olive stones or spreading pomace are examples of this. This result highlights how investment outlay is a limitation to circular approaches, which can also be solved through the adoption of specific government-type investment support measures. In terms of profit, circular scenarios achieve better performance related to the reduction of virgin raw materials purchased and the sale of some by-products such as olive pits. From the perspective of external cost evaluation, the circular scenario also shows the best results compared to the linear scenario. The climate change category achieved the lowest environmental costs due to lower emissions for fertilizer production.

Through the integrated analysis of economic and environmental results along with the assessment of circularity, it was possible to define the trade-offs that potentially exist in the implementation of closed-loop strategies, by considering the interrelation between improved circularity and changes in environmental and economic sustainability performances. Future research will be aimed at extending the analysis here proposed to other olive production areas to validate the applicability and effectiveness of circular strategies on olive-oil farms. In addition, further research development will be concerned with extending the sustainability dimensions by integrating the social-LCA (SLCA) methodology.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

GF, TS, AD, and ES: conceptualization. GF, TS, ES, and NI: data curation. GF, TS, ES, NI, and BB: formal analysis. AD: funding acquisition, project administration, and supervision. GF, TS, NI, AD, ES, and BB: investigation. GF, TS, AD, ES, and NI: methodology and writing—original draft. GG, BB, and AD: writing—review and editing. All authors contributed to the article and approved the submitted version.

Funding

This research was part of DRASTIC PRIN 2017 research project, project code: 2017JYRZFF, funded by the Italian Ministry of Education, University, and Research (MIUR).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Albuquerque, T. L. M., Mattos, C. A., Scur, G., and Kissimoto, K. (2019). Life Cycle Costing and externalities to analyze circular economy strategy: comparison between aluminum packaging and tinplate. *J. Clean. Prod.* 234:477–486. doi: 10.1016/j.jclepro.2019.06.091

Ben Abdallah, S., Parra-López, C., Elfkih, S., Elisa, M., Suárez-Rey, E. M., and Romero-Gámez, M. (2022). Sustainability assessment of traditional, intensive and highly-intensive olive growing systems in Tunisia by integrating Life Cycle and multicriteria decision analyses. *Sustain. Prod. Consum.* 33:73–87. doi: 10.1016/j.spc.2022.06.022

Benalia, S., Falcone, G., Stillitano, T., De Luca, A., Strano, A., Gulisano, G., et al. (2021). Increasing the content of olive mill wastewater in biogas reactors for a sustainable recovery: methane productivity and Life Cycle analyses of the process. *Foods* 10:1029. doi: 10.3390/foods10051029

Bernardi, B., Falcone, G., Stillitano, T., Benalia, S., Bacenetti, J., and De Luca, A. I. (2021). Harvesting system sustainability in Mediterranean olive cultivation: other principal cultivar. *Sci. Total Environ.* 766:142508. doi: 10.1016/j.scitotenv.2020.142508

Bradley, R., Jawahir, I. S., Badurdeen, F., and Rouch, K. (2018). A total life cycle cost model (TLCCM) for the circular economy and its application to post-recovery resource allocation. *Resour. Conserv. Recycl.* 135:141–149. doi: 10.1016/j.resconrec.2018.01.017

Cembalo, L., Borrello, M., De Luca, A. I., Giannoccaro, G., and D'Amico, M. (2020). Transitioning agri-food systems into circular economy trajectories. *Aestimum* 199–218. doi: 10.13128/aestim-8860

Chiaraluce, G. (2022). Circular economy in the agri-food sector: a policy overview. *Ital. Rev. Agric. Econ.* 76:53–60. doi: 10.36253/rea-13375

de Bruyn, S., Bijleveld, M., de Graaff, L., Schep, E., Schroten, A., Vergeer, R., et al. (2018). *Environmental Prices. Handbook EU28 Version*. Delft: CE Delft.

De Luca, A. I., Falcone, G., Stillitano, T., Iofrida, N., Strano, A., and Gulisano, G. (2018). Evaluation of sustainable innovations in olive growing systems: a Life Cycle sustainability assessment case study in southern Italy. *J. Clean. Prod.* 171:1187–1202. doi: 10.1016/j.jclepro.2017.10.119

Durão, V., Silvestre, J. D., Mateus, R., and De Brito, J. (2019). Economic valuation of life cycle environmental impacts of construction products - A critical analysis. *IOP Conf. Ser.: Earth Environ. Sci.* 323, 012147. doi: 10.1088/1755-1315/323/1/012147

Ellen MacArthur Foundation (2015). *Circularity Indicators. An Approach to Measuring Circularity*. EMF: Cowes.

EPD (2017). *Environmental Product Declaration (EPD) of Extra Virgin Olive Oil from the De Cecco Company*. Registration number S-P-00410 (Revision date: 17 July, 2017).

EPD (2022). *Environmental Product Declaration (EPD) of Extra Virgin Olive Oil "GranFruttato" Monini S.p.A.* Registration number S-P-00383 (Revision date: 16 February, 2022).

Estévez, S., González-García, S., Feijoo, G., and Moreira, M. T. (2022). How decentralized treatment can contribute to the symbiosis between environmental protection and resource recovery. *Sci. Total Environ.* 812:151485. doi: 10.1016/j.scitotenv.2021.151485

Foti, P., Pino, A., Romeo, F. V., Vaccalluzzo, A., Caggia, C., and Randazzo, C. L. (2022). Olive pomace and pâté olive cake as suitable ingredients for food and feed. *Microorganisms* 10:237. doi: 10.3390/microorganisms10020237

Goddin, J., Marshall, K., Pereira, A., and Herrmann, S. (2019). *Circularity Indicators—An Approach to Measuring Circularity. Methodology*. Wilmington: The Ellen MacArthur Foundation.

Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., and Meijer, E. (2013). *Introduction to LCA with SimaPro.* Netherlands: *PRè—Product Ecology* Consultants.

Gómez-Muñoz, B., Valero-Valenzuela, J. D., Hinojosa, M. B., and García-Ruiz, R. (2016). Management of tree pruning residues to improve soil organic carbon in olive groves. *Eur. J. Soil Biol.* 74:104–113. doi: 10.1016/j.ejsobi.2016.03.010

Guarino, F., Falcone, G., Stillitano, T., De Luca, A. I., Gulisano, G., Mistretta, M., et al. (2019). Life cycle assessment of olive oil: a case study in southern Italy. *J. Environ. Manage.* 238:396–407. doi: 10.1016/j.jenvman.2019.03.006

Hamam, M., Di Vita, G., Zanchini, R., Spina, D., Raimondo, M., Pilato, M., et al. (2022). Consumers' attitudes and purchase intention for a vitamin-enriched extra virgin olive oil. *Nutrients* 14:1658. doi: 10.3390/nu14081658

Hauschild, M. Z., Rosenbaum, R. K., and Olsen, S. I., (Eds.). (2018). *Life Cycle Assessment—Theory and Practice*. Switzerland: Springer International Publishing AG. doi: 10.1007/978-3-319-56475-3

Heijungs, R., Settanni, E., and Guinée, J. (2013). Toward a computational structure for life cycle sustainability analysis: unifying LCA and LCC. *Int. J. Life Cycle Assess.* 18:1722–1733. doi: 10.1007/s11367-012-0461-4

Hermoso-Orzáez, M. J., Mota-Panizio, R., Carmo-Calado, L., and Brito, P. (2020). Thermochemical and economic analysis for energy recovery by the gasification of WEEE plastic waste from the disassembly of large-scale outdoor obsolete luminaires by LEDs in the alto alentejo region (Portugal). *Appl. Sci.* 10:4601. doi: 10.3390/app10134601

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., et al. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* 22:138–147. doi: 10.1007/s11367-016-1246-y

Hussain, M., Mumma, G., and Saboor, A. (2005). Discount rate for investments: some basic considerations in selecting a discount rate. *Pak. J. Life Soc.* Sci. 3, 1–5.

IOC (2021). *International Olive Council. EU Olive Oil Figures*. Available online at: https://www.internationaloliveoil.org/wp-content/uploads/2021/12/HO-CE901-17-12-2021-P.pdf (accessed July 18, 2021).

ISMEA. (2022). *Tendenze e dinamiche recenti. Olio d'oliva - Settembre 2022.* IsmeaMercati.

ISO (2021a). *ISO 14040:2021Environmental Management—Life Cycle Assessment—Principles and Framework.* Geneva: International Organization for Standardization.

ISO (2021b). *ISO 14044:2021Environmental Management—Life Cycle Assessment—Requirements and Guidelines.* Geneva: International Organization for Standardization.

ISTAT (2021). *Istituto Nazionale di Statistica. Italian Olive Oil.* Available online at: http://dati.istat.it/Index.aspx?QueryId=37850 (accessed July 18, 2021).

Kerdlap, P., and Cornago, S. (2021). "Life cycle costing: methodology and applications in a circular economy," in *An Introduction to Circular Economy*, eds L. Liu and S. Ramakrishna (Singapore: Springer Nature), 499–525. doi: 10.1007/978-981-15-8510-4_25

Klöpffer, W., and Renner, I. (2008). "Life-cycle based sustainability assessment of products," in *Environmental Management Accounting for Cleaner Production*, eds S. Schaltegger, M. Bennett, R. L. Burritt, C. Jasch. (Heidelberg: Springer Science + Business Media B.V.), 91–102. doi: 10.1007/978-1-4020-8913-8_5

Mastoras, P., Vakalis, S., Fountoulakis, M. S., Gatidou, G., Katsianou, P., Koulis, G., et al. (2022). Evaluation of the performance of a pilot-scale solar still for olive mill wastewater treatment. *J. Clean. Prod*. 365:132695. doi: 10.1016/j.jclepro.2022.132695

Mayanti, B., and Helo, P. (2022). Closed-loop supply chain potential of agricultural plastic waste: economic and environmental assessment of bale wrap waste recycling in Finland. *Int. J. Prod. Econ*. 244:108347. doi: 10.1016/j.ijpe.2021.108347

Moreno, L., Gonz?lez, A., Cuadros-Salcedo, F., and Cuadros-Blázquez, F. (2017). Feasibility of a novel use for agroindustrial biogas. *J. Clean. Prod*. 144, 48–56. doi: 10.1016/j.jclepro.2016.12.060

Ncube, A., Fiorentino, G., Panfilo, C., Maria De Falco, M., and Ulgiati, S. (2022). Circular economy paths in the olive oil industry: a Life Cycle Assessment look into environmental performance and benefits. *Int. J. Life Cycle Assess.* doi: 10.1007/s11367-022-02031-2

Nemecek, T., and Kägi, T. (2007). *Life Cycle Inventories of Swiss and European Agricultural Production Systems*. Final Report Ecoinvent V2.0 No. 15a. Agroscope Reckenholz-Taenikon Research Station ART, Swiss Centre of Life Cycle Inventories: Zurich and Dübendorf.

Niero, M., and Kalbar, P. P. (2019). Coupling Material Circularity Indicators and life cycle based indicators: a proposal to advance the assessment of circular economy strategies at the product level. *Resour. Conserv. Recycl*. 140:305–312. doi: 10.1016/j.resconrec.2018.10.002

Prasuhn, V. (2006). *Erfassung der PO4- Austräge für die Ökobilanzierung—SALCA-Phosphor*. Zürich: Agroscope FAL Reckenholz.

Rocchi, L., Paolotti, L., Cortina, C., Fagioli, F. F., and Boggia, A. (2021). Measuring circularity: an application of modified Material Circularity Indicator to agricultural systems. *Agric. Food Econ*. 9:9. doi: 10.1186/s40100-021-00182-8

Rödger, J. M., Kjær, L. L., and Pagoropoulos, A. (2018). "Life cycle costing: an introduction," in *Life Cycle Assessment: Theory And Practice,* eds M. Z. Hauschild, R. K. Rosenbaum, S. I. Olsen, Cham: Springer, 373–400. doi: 10.1007/978-3-319-56475-3_15

Roos Lindgreen, E., Opferkuch, K., Walker, A. M., Salomone, R., Reyes, T., Raggi, A., et al. (2022). Exploring assessment practices of companies actively engaged with circular economy. *Bus. Strategy Environ* 31:1414–1438. doi: 10.1002/bse.2962

Rufí-Salís, M., Petit-Boix, A., Villalba, G., Gabarrell, X., and Leipold, S. (2021). Combining LCA and circularity assessments in complex production systems: the case of urban agriculture. *Resour. Conserv. Recycl*. 166:105359. doi: 10.1016/j.resconrec.2020.105359

Silvestri, C., Silvestri, L., Piccarozzi, M., and Ruggieri, A. (2022). Toward a framework for selecting indicators of measuring sustainability and circular economy in the agri-food sector: a systematic literature review. *Int. J. Life Cycle Assess.* doi: 10.1007/s11367-022-02032-1

Stempfle, S., Carlucci, D., De Gennaro, B. C., Roselli, L., and Giannoccaro, G. (2021). Available pathways for operationalizing circular economy into the olive oil supply chain: mapping evidence from a scoping literature review. *Sustainability* 13:9789. doi: 10.3390/su13179789

Stillitano, T., Falcone, G., De Luca, A. I., Piga, A., Conte, P., Strano, A., et al. (2019). A life cycle perspective to assess the environmental and economic impacts of innovative technologies in extra virgin olive oil extraction. *Foods* 8:209. doi: 10.3390/foods8060209

Stillitano, T., Falcone, G., Iofrida, N., Spada, E., Gulisano, G., and De Luca, A. I. (2022). A customized multi-cycle model for measuring the sustainability of circular pathways in agri-food supply chains. *Sci. Total Environ*. 844:157229. doi: 10.1016/j.scitotenv.2022.157229

Stillitano, T., Spada, E., Iofrida, N., Falcone, G., and De Luca, A. I. (2021). Sustainable agri-food processes and circular economy pathways in a life cycle perspective: state of the art of applicative research. *Sustainability* 13:2472. doi: 10.3390/su13052472

Taguas, E. V., Marín-Moreno, V., Díez, C. M., Mateos, L., Barranco, D., Francisco-Javier Mesas-Carrascosa, Pérez, R., et al. (2021). Opportunities of super high-density olive orchard to improve soil quality: management guidelines for application of pruning residues. *J. Environ. Manage*. 293:112785. doi: 10.1016/j.jenvman.2021.112785

Tse, K. K., Chow, T. T., and Su, Y. (2016). Performance evaluation and economic analysis of a full scale water-based photo-voltaic/thermal (PV/T) system in an office building. *Energy Build*. 122:42–52. doi: 10.1016/j.enbuild.2016.04.014

United Nations (2022). *World Population Prospects 2022*. Available online at: https://population.un.org/wpp/ (accessed 25 July, 2022). doi: 10.18356/9789210014380

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., et al. (2013). *Overview and Methodology. Data Quality Guideline for the Ecoinvent Database Version 3. Ecoinvent Report 1(v3)*. St. Gallen: The ecoinvent Centre.

Zampori, L., and Pant, R. (2019). *Suggestions for Updating the Organisation Environmental Footprint (OEF) Method, EUR 29681 EN*. Luxembourg: Publications Office of the European Union. ISBN 978-92-76-00651-0, JRC115960.

Zanchini, R., Di Vita, G., Spina, D., De Luca, A. I., and D'Amico, M. (2022). Eliciting consumers' health consciousness and price-related determinants for polyphenol-enriched olive oil. *NJAS Impact Agric. Life Sci.* 94:47–79. doi: 10.1080/27685241.2022.2108733

frontiers | Frontiers in Sustainable Food Systems

TYPE Systematic Review
PUBLISHED 12 January 2023
DOI 10.3389/fsufs.2022.1012436

Check for updates

OPEN ACCESS

EDITED BY
Maurizio Cellura,
University of Palermo, Italy

REVIEWED BY
Štefan Bojnec,
University of Primorska, Slovenia
Giulia Maesano,
University of Verona, Italy

*CORRESPONDENCE
Daniela Spina
danispina@gmail.com

SPECIALTY SECTION
This article was submitted to Waste Management in Agroecosystems, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 05 August 2022
ACCEPTED 10 October 2022
PUBLISHED 12 January 2023

CITATION
Hamam M, Spina D, Raimondo M, Di Vita G, Zanchini R, Chinnici G, Tóth J and D'Amico M (2023) Industrial symbiosis and agri-food system: Themes, links, and relationships. *Front. Sustain. Food Syst.* 6:1012436. doi: 10.3389/fsufs.2022.1012436

Industrial symbiosis and agri-food system: Themes, links, and relationships

Manal Hamam[1], Daniela Spina[1]*, Maria Raimondo[1], Giuseppe Di Vita[2], Raffaele Zanchini[2], Gaetano Chinnici[1], József Tóth[3,4] and Mario D'Amico[1]

[1]Department of Agriculture, Food and Environment, University of Catania, Catania, Italy, [2]Department of Agricultural, Forest and Food Sciences, University of Turin, Turin, Italy, [3]Department of Agricultural Economics, Corvinus University of Budapest, Budapest, Hungary, [4]Faculty of Economics, Socio-Human Sciences and Engineering, Sapientia Hungarian University of Transylvania, Cluj-Napoca, Romania

Industrial symbiosis is an eco-innovative system concept that is based on a circular economy and industrial ecology ideas. This process comprises the movement of materials, energy, and skills across enterprises located within eco-industrial parks, and strives to provide economic, environmental, and social competitive advantages for all the involved parties. Considering that the agri-food system creates a vast quantity of by-products along the supply chain, it is a sector that has huge potential within material and energy recovery systems and fits well into eco-industrial parks. The current study is a literature review that aims to evaluate the interest exhibited so far by scientific research in the topic of industrial symbiosis in the agri-food sector and to highlight the primary analytical techniques that have been used for this topic. Using the paradigm of multiple correspondence analysis, a content analysis was conducted from which the major themes of the researched phenomena emerged. The results indicate that the topic areas are unrelated and somewhat distant from each other. The analyzed case studies have revealed that the authors had neglected the communicative and collaborative elements among stakeholders, and instead focused on the potential use of some tools and approaches. Furthermore, it has been hypothesized that the hiding of information within a supply chain prevents industrial symbiosis procedures from being implemented. This research suggests the necessity of creating communication and cooperation platforms among stakeholders, which would promote the introduction of new techniques and tools for the development of circular production systems.

KEYWORDS
industrial symbiosis, industrial ecology, circular economy, agri-food, content analysis, MCA

1. Introduction

The influence of the existing global agri-food system poses a threat to local ecosystems (Willett et al., 2019). The current agri-food production practices in developed nations are marked by industrialized and intensive agriculture, market-oriented production, and high water and energy usage (Senauer and Venturini, 2005).

As a result of the ongoing changes in land use, in CO_2 emissions, energy and water consumption, and in chemical pollution, the continuous growth in the amount and quality of output required to sustain an appropriate level of nourishment has had detrimental effects (Di Vita et al., 2017; Willett et al., 2019).

As food-production areas have reached their maximum capacity (Dubois, 2011), innovative cultivation, production, and consumption methods that include a radical transformation of the system are required (Herrero et al., 2020).

A shift in food production and processing practices has the potential of being a powerful driver of the local and global transition to sustainable development (Willett et al., 2019).

In this regard, governments, businesses, research institutes, and non-governmental organizations (NGOs) are exploring new ways of reusing products, their components, and waste material through the adoption of closed-loop systems that are aimed at improving economic and environmental sustainability (Toop et al., 2017; Duque-Acevedo et al., 2020).

The notion of circular economy (CE) is seen as the guiding principle of eco-innovation (Hamam et al., 2021, 2022), which is aimed at achieving a zero-waste society and economy, whose raw materials are utilized to create new goods and uses.

However, CE is viewed as an "umbrella concept" (Blomsma and Brennan, 2017) which encompasses a variety of phenomena that promote closed-loop systems (Prieto-Sandoval et al., 2018), such as industrial ecology (IE), industrial ecosystems and industrial symbiosis (IS), natural capitalism, cradle-to-cradle, blue economy, biomimicry, and regenerative design (Prieto-Sandoval et al., 2018; Sehnem et al., 2019; Unay-Gailhard and Bojnec, 2019).

Although the circular economy is considered as a restorative system, the associated ideas are viewed as preventative systems that require efforts to reduce energy and material losses and/or optimize them inside the system (Borrello et al., 2020; Cembalo et al., 2020; Al-Thani and Al-Ansari, 2021; Atanasovska et al., 2022).

The development of CE would not be conceivable without IE ideas and techniques (Saavedra et al., 2018), and in particular the use of industrial symbiosis processes (Herczeg et al., 2018).

In fact, a circular economy encourages the development of the concept of industrial symbiosis (IS), which is an eco-innovative system approach that involves the transfer of such resources as matter, energy, water, by-products, skills, and competencies between traditionally separate industries to generate competitive advantages for all the involved territorial actors (Chertow, 2000; Graedel and Allenby, 2003; Haller et al., 2022).

The symbiosis process develops through systems of cooperation and synergies between different industrial enterprises, as well as through various resource exchange mechanisms at a local scale to support the transition to a circular economy (Imbert, 2017; Kalmykova et al., 2018; Kerdlap et al., 2019), so that the waste and/or by-products of one enterprise can become the input of another (Mulrow et al., 2017).

The distance between the waste producer and the potential consumer is in fact one of the most important economic factors that should be considered when assessing the viability of symbiosis (Marchi et al., 2017; Aschemann-Witzel and Stangherlin, 2021). However, if the cost of transit remains the same and is more than the cost of purchasing raw materials, a circular system cannot function.

IS, despite its complexity, has been applied in agriculture, aquaculture, and animal husbandry (Dumont et al., 2013; Alfaro and Miller, 2014).

The application of an industrial symbiosis process to agri-food supply chains represents a significant opportunity for systemic changes in various components of the food system, such as technologies, infrastructure, skills, and knowledge (Abson et al., 2017; Parker and Svantemark, 2019; Herrero et al., 2020; Poponi et al., 2022; Stillitano et al., 2022), as well as for the creation of interactions between economic agents within a district (Nowak et al., 2015; Unay-Gailhard and Bojnec, 2016).

In line with this, industrial symbiosis facilitation tools that use information and communication technology, as well as network optimisation techniques, have been created to uncover synergistic connections between industrial processes and businesses (Grant et al., 2010; Boix et al., 2015; Kastner et al., 2015; Fraccascia et al., 2016; Van Capelleveen et al., 2018; Yeo et al., 2019; Raimbault et al., 2020).

This is one of the first studies to have conducted a literature review on the issues and major research subjects linked to the idea of industrial symbiosis in the agri-food field. The aim of this review has been to help provide a baseline for the development of strategies that will lead to the creation of more environmentally, financially and socially sustainable industrial technologies and processes.

This work addresses the following research question:

(RQ1) What are the main themes and the main interrelations that are emerging from the link between industrial symbiosis and agribusiness system?
(RQ2) Does a true relationship exist between these systems?

A content analysis was undertaken using the text mining WordStat programme and the "bibliometrix" R package to facilitate the synthesis of qualitative data. This computer-assisted synthesis of the literature made it possible to identify the major research topics of the articles, as well as their interrelationships, and to obtain a holistic interpretation of the reference framework pertaining to the examined phenomena.

On the basis of the data analysis, the authors then developed a set of research-based suggestions that could be further explored in future studies. They thus proposed set of recommendations for researchers and policymakers to promote symbiotic exchange, and identified the tools currently available in industrial symbiosis cases so that all stakeholders can recognize the tangible benefits of this business model and engage economically in promoting its implementation.

The remainder of the paper is structured as follows: Section Agro-Ecological symbiosis strategies offers an assessment of the literature on agro-ecological symbiosis strategies. The methodology is described and the results are analyzed in Sections Methodology and Results. The implications of the results are discussed in Section Discussion and recommendations are provided for further research. The concluding remarks are provided in the last section.

2. Agro-Ecological symbiosis strategies

2.1. Industrial ecology

Industrial ecology (IE) is a study and practice discipline that arose in the 1990s, which focuses on the establishment and management of a closed-loop industrial environment (Saavedra et al., 2018; Baldassarre et al., 2019; Al-Thani and Al-Ansari, 2021).

It examines the relationships that exist between industrial systems and the natural environment (Garner and Keoleian, 1995) to achieve economic, social, and environmental harmony (Trokanas et al., 2014), and proposes approaches and applied solutions for a more efficient management of material and energy flows in companies (Simboli et al., 2015).

Industrial ecosystems were described by Frosch and Gallopolus (1989), as a system in which "the consumption of energy and materials is optimized, and the effluents of one process serve as raw material for another process." In fact, they hypothesized that an industrial system can learn about efficiency by watching the material and energy movements of natural ecosystems (Frosch and Gallopolus, 1989).

A few years later, in 1995, Graedel and Allenby (1995) were the first to describe EI as a mechanism that could be used to achieve an economic, cultural, and technical expansion, while preserving the carrying capacity of the environment.

Its goals include not only the optimisation of energy and material consumption, but also the reduction of waste and of the resulting contamination of the natural environment, *via* the transformation of waste and industrial by-products into inputs for other processes (Trokanas et al., 2014; Beaulieu, 2015).

Specifically, the concept of IE encompasses five elements: dematerialisation; long-term policy alignment; the creation of industrial ecosystems; industrial metabolism, which is defined as the transformation of a linear economic system into an integrated industrial ecosystem (Frosch and Gallopolus, 1989; Prendeville et al., 2018), i.e., an analysis of the flow of materials and energy that spans the entire life cycle of a particular product; and balancing inputs and outputs.

The primary applications of IE-based solutions in the agro-food sector include animal and vegetable waste, and by-products (Mirabella et al., 2014; Simboli et al., 2015).

IE concepts and tools may function at several levels, including the farm, local, regional, and supra-regional levels (Figure 1), with the goal of decreasing environmental effects at each step of production and consumption. Many of these techniques concentrate on "closing the loop" of material flows and rely on recovery and recycling (Despeisse et al., 2012); others include product and process design and technology, organizational and management strategies, and government activities (Frosch and Gallopolus, 1989; Allenby, 1996; Ayres and Ayres, 1996; Erkman, 1997).

At the inter-firm level, industrial symbiosis is the process of promoting the evolution of synergy networks between different organizations (Chertow, 2000) and the efficiency of the physical exchange of materials and resources, including energy, water, and by-products, in the local and regional industrial ecosystem (Chertow, 2007; Li, 2018).

2.2. Industrial symbiosis in agri-food

Industrial symbiosis (IS) is a progression of the industrial ecosystem idea, which Frosch and Gallopoulos initially introduced in 1989. It adheres to the concepts of industrial ecology, that is, to promote developing sustainable methods to boost production cycle efficiency and reduce the usage of non-renewable resources (Pagotto and Halog, 2016).

Consequently, it identifies business opportunities (Mantese and Amaral, 2018) that leverage on the synergistic exchange of such resources as water, energy, material flows, residues, waste, and under-utilized by-products (Chertow, 2000; Lombardi and Laybourn, 2012) between actors in co-located companies (Chertow et al., 2004; Wolf et al., 2007; Simboli et al., 2015; De Angelis et al., 2018; Mantese and Amaral, 2018; Yenipazarli, 2019).

The execution of an IS project can have several positive effects, not only from an environmental point of view, but also socially and economically (Neves et al., 2020). The environmental benefits are primarily related to the reduction of the impacts associated with waste disposal processes and methods, as well as the extraction and importing of virgin

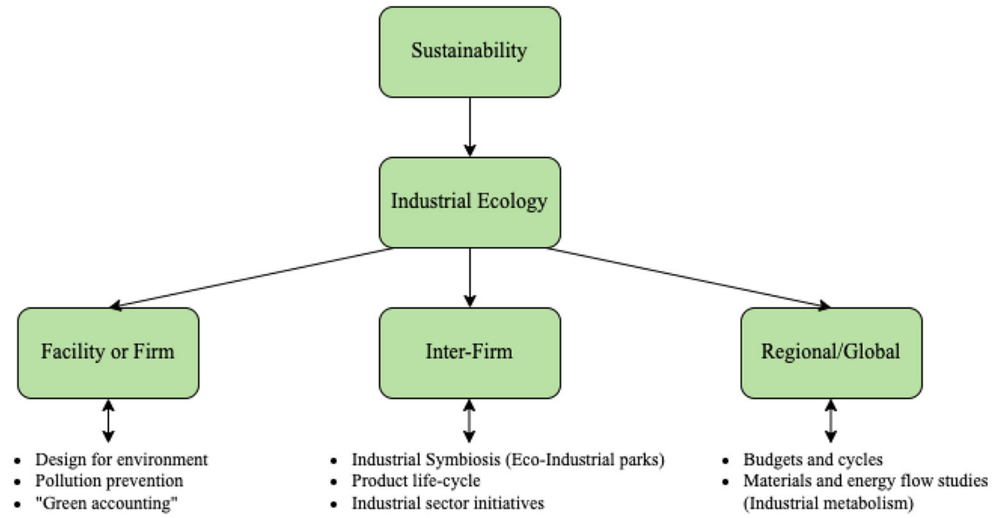


FIGURE 1
Industrial ecology structure. Source: Chertow (2000).

raw materials, which result in greenhouse gas emissions, the depletion of natural resources, and waste that would otherwise end up in landfills and incinerators.

These effects, which are verifiable at several levels, demonstrate that developing synergy is not only an exchange or pooling of resources, but also a new value generation process for all the involved parties. Consequently, the global value generated through such a synergy will be larger than the value provided by organizations working separately (Lowe, 1997).

The social advantages are a result of the development of new employment through the processing of leftovers and by-products, and the valorisation of labor resources through decreased raw material prices.

In addition to social and environmental advantages, an IS project also results in economic gains, due to a decreased cost of the raw materials and waste treatment.

Resource sharing may occur in three ways: by-product exchange, service/infrastructure sharing, or shared service purchase (Ehrenfeld and Gertler, 1997; Mirata and Emtairah, 2005; Chertow, 2007).

By-product reuse is simply an interchange of industrial material flows between two or more businesses, in which any surplus material from one operation is utilized to substitute raw materials or commercial goods in the other (Walmsley et al., 2019). Service/infrastructure sharing refers to the joint management and use of essential resources, including water, electricity, and wastewater. Similarly, the collaborative supply of services includes coordination, such as shared transit arrangements, food provision, and other requirements shared by neighboring firms and industries (Chertow, 2007).

However, this should entail the participation and interaction of historically different sectors, if the aim is to develop an integrated and collective strategy to interchange resource flows, create competitive advantage, and maximize resource efficiency (Chertow, 2000).

Chertow (2007), in order to differentiate industrial symbiosis from other types of exchange, considered a "3–2 heuristic," which recognizes complex relationships in which at least three distinct entities should be involved in the exchange of at least two distinct resources, none of which should be engaged in recycling.

In addition, one of the characteristics of industrial symbiosis is the capacity to consider different types of industries, including not only farms, but also their upstream and downstream partners (Fernandez-Mena et al., 2016), and to make their specific input requirements and supply capacities explicit. An additional benefit of these systems is their ability to handle a variety of convertible materials, chemicals, and energy fluxes. It is possible to design locally effective recycling cycles by analyzing how and to what extent these various resources are handled, created, and changed within agent clusters (Fernandez-Mena et al., 2016).

Companies may employ internal IS strategies, whereby waste from one production process is used to replace virgin raw material inputs in other production processes inside the firm, or external IS strategies, whereby waste is sent to other companies that will then utilize it in their manufacturing processes (Fraccascia et al., 2016).

Yu et al. (2014) provided a summary of the recent advancements in industrial symbiosis procedures. From 1997 to 2005, scientific research on industrial symbiosis (IS) comprised just a small portion of the Industrial Ecology (IE) literature and focused on the concept of IS, the evaluation of eco-industrial park (EIP) projects (Garner and Keoleian, 1995), and the development of waste treatment and recycling networks.

Cases of industrial symbiosis may be split into three distinct categories: (1) area symbiosis, that is, the experiences of industrial symbiosis districts (bottom-up), such as those of Kalundborg, Denmark, or Eco-industrial Parks, which are characterized by the implementation, in more or less extensive territorial areas, of several subjects which, over time, carry out specific interventions for the closure and optimisation of cycles; (2) networked symbiosis, i.e., cases of industrial symbiosis based on cognitive/relational tools intended to facilitate the meeting between the demand and supply of resources (matter, energy, water, by-products, capacity, skills) between interlocutors whose economic and social activities would not otherwise have the chance to take place; (3) resource diagnostics, i.e., programmes that attempt to map business resources and find internal efficiency improvement solutions, as well as to enable the identification of potential input and output synergies with external interlocutors. A business that follows this route should conduct an integrated study of its resource management system in order to achieve internal and external efficiency benefits.

Organic substances have rarely been the subject of investigation in classic cases of industrial symbiosis. However, the concept may also be extended to agri-food chains and energy systems (Koppelmäki et al., 2019; Onu and Mbohwa, 2021).

The term “agroecological symbiosis” (AES) was first used for the redesign of a production system in the Finnish town of Palopuro (Koppelmäki et al., 2016). It is derived from the concept of industrial symbiosis applied to the food production and processing chain that operates with renewable energy, derived from its own raw materials, and in which farms, food processors, and energy producers operate in an integrated manner (Helenius et al., 2020), thereby strengthening local socio-economic ties.

When applying the concept of industrial symbiosis in the food processing sector, the first step is the identification, quantification, and characterization of residues, which are typically by-products or waste from biorefineries, agro-industries, or bio-oriented chemical industries (Ehrenfeld and Gertler, 1997; Van Beers et al., 2007), and then the determining of the recovery steps and technologies that can be applied for their processing (Galanakis, 2012).

There are instances in the literature (Zabaniotou et al., 2015) of systems that were built on a circular economy and industrial symbiosis framework in firms, such as the study of Pagotto and Halog (2016), who used input-output methodologies to analyse the Australian agri-food sector.

Industrial symbiosis is a crucial instrument for industrial activities in geographic regions where several enterprises may collaborate synergistically to produce more sustainably.

The transfer of resources from one firm to another provide economic benefits: the transferring company obtains a reduction in yearly waste management expenses and a profit upon sale, while the receiving company experiences a decrease in production costs.

3. Methodology

3.1. Data sources

The objective of the literature review was to select relevant research from the academic literature and synthesize the important findings on industrial symbiosis in the agricultural field Figure 2 shows a Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) flowchart to illustrate how the selection criteria were created using a systematic and repeatable process to identify articles that explored the topic (Maesano et al., 2022).

The literature review was undertaken by searching the Scopus and Web of Science (WoS) databases for pertinent papers.

The following keywords were used to extract articles published between 2007 and 2022: “industrial symbiosis” AND “agri-food” OR “agrifood” OR “agro-food” OR “agrofood” OR “food.” The search was run in May 2022 on titles, abstracts, and keywords, without any regard for the year. A total of 87 Scopus articles and 96 WoS papers, for a total of 183, were found and then submitted to a selection process.

The exclusion criteria included books, chapters, proceedings, editorials, and studies (31). In addition, any duplicates (93) and non-English language items (4) were removed. In all, 55 studies were ultimately considered.

A thorough search revealed that 55 publications satisfied the inclusion criteria, i.e., case studies and reviews, for the purpose of this study’s literature review.

3.2. Data analysis

3.2.1. Multiple correspondence analysis

The authors first proposed a representation of the evolution of the publications over time, the most frequent keywords over the years, and a classification of the scientific papers.

Subsequently, to find the primary issues, a multiple correspondence analysis (MCA) was used to identify the reoccurring themes of the articles.

The overall conceptual framework of industrial symbiosis research in the agri-food industry was investigated using k-means clustering and correspondence analysis (Mitsuhiro and Yadohisa, 2015). Multiple correspondence analysis (MCA) is a multidimensional statistical approach that dates back to

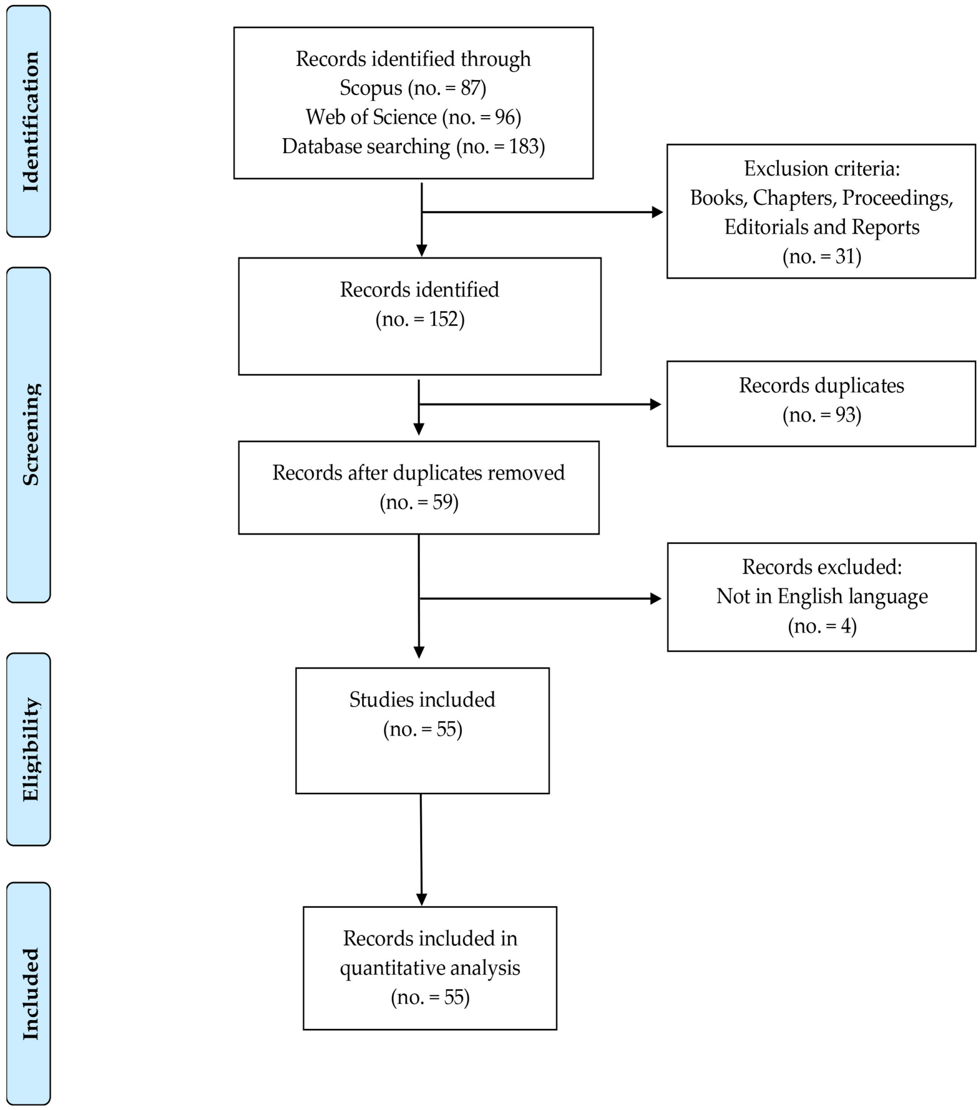


FIGURE 2
Flowchart of the database literature research. Source: our elaboration.

Hirschfeld (1935) and it is commonly utilized in marketing, and in particular for multidimensional mapping (Raimondo et al., 2022).

Through a graphical representation of a data matrix of qualitative variables, it is presented as a paradigm for exploratory bibliometric analysis to assess the dependency between keywords and discover clusters (Batagelj and Cerinšek, 2013).

The research was conducted using the "bibliometrix" R package (Aria and Cuccurullo, 2017), which enabled us to input text files and generate a data matrix, a conceptual structure map, and a dendrogram. "Keywords Plus" was used as input for the study as it includes fewer content-specific descriptors of the articles and, therefore, conveys wider meanings, thus making it acceptable for conceptual structure analysis. A k-means clustering technique was used for the data to determine the clusters in the MCA-obtained conceptual framework.

3.2.2. Co-occurrence network

Co-occurrence analyses were conducted for the keywords and clusters to determine the strength of the relationships between the keywords and clusters that had emerged.

Co-occurrence analysis is an well-known technique that is used for mapping scientific knowledge (Radhakrishnan et al., 2017; Spina et al., 2021; Vindigni et al., 2021; Bellia et al., 2022), in which words or categories that tend to be repeated together are combined through a clustering process.

Each keyword is represented by a node, and a link between two nodes indicates their co-occurrence.

The frequency with which two keywords are used together is therefore illustrated by the weight of an edge. By applying network clustering algorithms, any mutual associations between them can be identified and illustrated.

4. Results

The rise in the number of publications on industrial symbiosis in the agri-food industry from 2002 to 2022 is shown in Figure 3.

Research on the phenomena was rarely conducted prior to 2019. However, the quantity of published papers has increased significantly since 2019. The graph demonstrates the correlation between the rise in publications on industrial symbiosis and the interest in closed-loop production systems and sustainability.

In fact, the European Commission launched the European Green Deal in that very year with the intention of turning the climate crisis into a chance for a new model of development. The aim was to become the first carbon-neutral continent by 2050 by means of a socially and just ecological transition and through an industrial revolution that could guarantee sustainable productions (European Commission, 2020). It is realistic to imagine that there will be more papers on these themes in the future, given the increased interest in these topics among scientists.

Figure 4 depicts a one-year log scale to illustrate the trends in the development and sustainability study themes over the previous decade.

The use of the terms "industrial symbiosis" and "industrial ecology" increased in 2015 and 2016, respectively. In 2019, the most frequent term was "waste management," followed by "food waste" in 2020 and "eco-industrial park" in 2021.

The analysis of the publications revealed that 29 publications were case studies, 17 were reviews, five were articles, two were full-length, one referred to hypothesis and theory, and one to decision assistance, as shown in Figure 5.

4.1. MCA results

Figure 6 represents the outcome of the multiple correspondence analysis as a map of the conceptual structure, which consists of five clusters: food supply chain, eco-industrial parks, life cycle assessment, greenhouse gas emissions, and anaerobic digestion, in relationship to the x and y axes.

MCA has two dimensions, one horizontal (x), and one vertical (y), which represent orthogonal latent dimensions.

The size of the map reflects the typical poles of the topical orientation within the industrial symbiosis concept, while the center of the map indicates the average location of all the keywords and, hence, the center of the search field. For instance, the terms "food waste," "waste management," and "circular economy" are located near to the center, since a significant number of publications on industrial symbiosis in the agri-food industry addressed these concerns.

Both of the latent dimensions are described by the fifty keywords that emerged from the research.

The total inertia, or total explained variability, is equal to the addition of the inertia of the two dimensions. The first dimension (x-axis) provides for most of the inertia (39.08%), while the second dimension (y-axis) contributes by 18.9%.

The first horizontal dimension divides the terms that emphasize production and emission processes (left) from those related to the management and recovery of by-products (right).

The second vertical dimension differentiates the keywords that emphasize heat processes due to emissions and waste recovery (at the top) from those that emphasize waste assessment and recovery systems (at the bottom).

The closeness between the keywords is proportional to the percentage of them that are mentioned together in the articles, while the greater the distance between them, the lower the proportion of keywords that are discussed together.

The figure enables linkages and disassociations to be determined between terms by analyzing their closeness.

The centroid concept guides the interpretation of the keyword points, according to which the keyword coordinates are the weighted average of the surrounding coordinates.

The dendrogram in Figure 7 illustrates the hierarchical link between clusters and variables. It is often generated for hierarchical clustering, and its primary use is to determine the optimal approach to allocate variables to clusters. The arrangement of keywords is based on how similar or distinct they are to one another and to other clusters.

As evaluated by Pearson's correlation coefficient, clusters that are nearly the same height are comparable, while clusters with differing heights are distinct.

As shown in the dendrogram, the clusters of anaerobic digestion, greenhouse gas emissions, the food supply chain, life cycle assessments, and eco-industrial parks are distinct, due to their differing branch lengths.

Figure 8 illustrates the keyword co-occurrence network. Industrial symbiosis and industrial ecology are the primary nodes, and they are followed by food waste, waste management, sustainable development, symbiosis, and environmental effects.

The co-occurrence network connecting the groups found by means of the multiple correspondence analysis is shown in Figure 9. The anaerobic digestion and food supply chain clusters often co-occur (3,451), as does the food supply chain with greenhouse gas emission cluster (4,253).

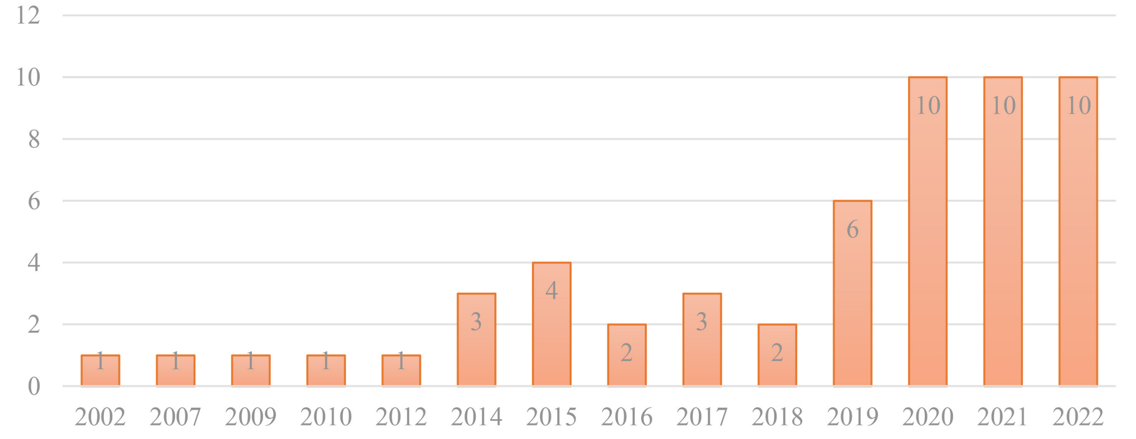


FIGURE 3
Evolution of publication from 2007 to 2022. Source: our elaboration.

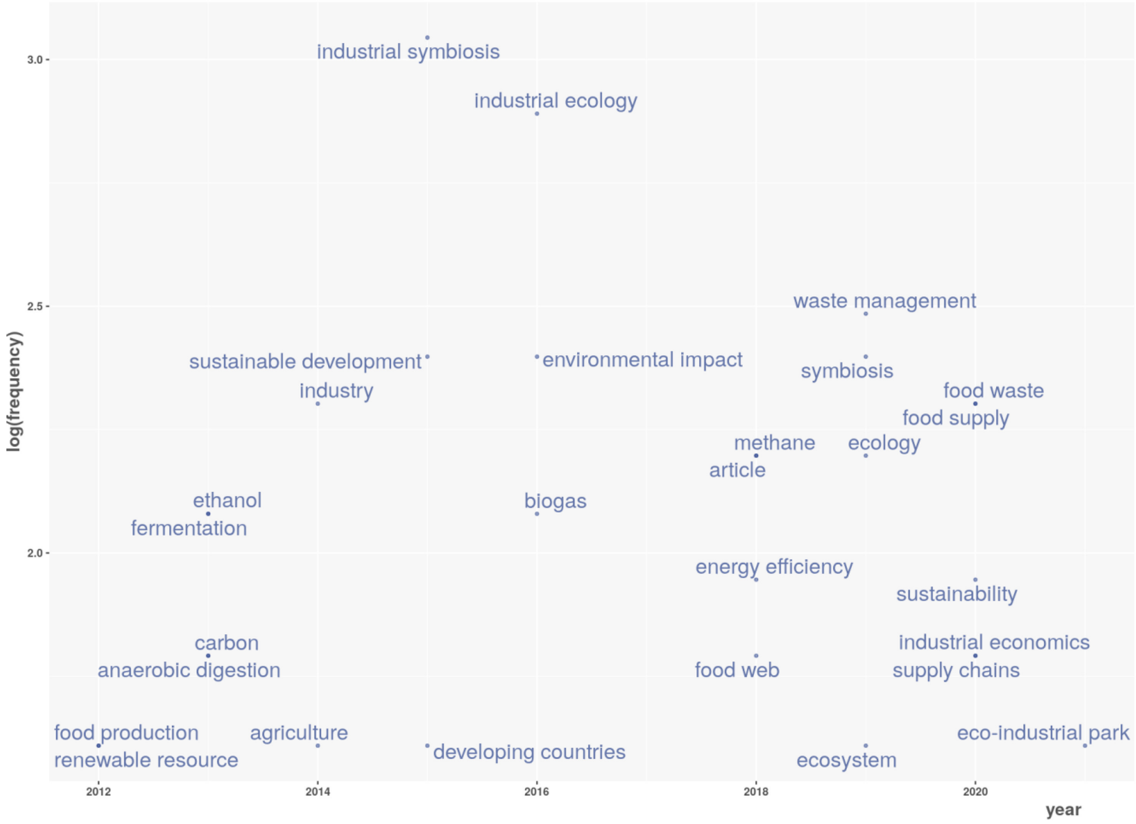


FIGURE 4
Trend keywords in the last 10 years. Source: our elaboration using "bibliometrix" R package.

10.3389/fsufs.2022.1012436

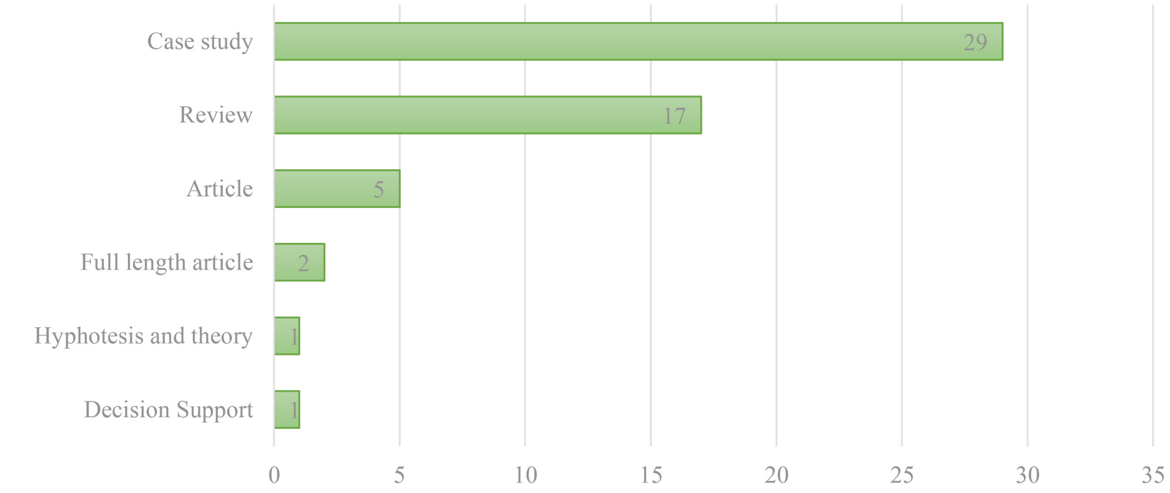


FIGURE 5
Classification of scientific papers. Source: our elaboration.

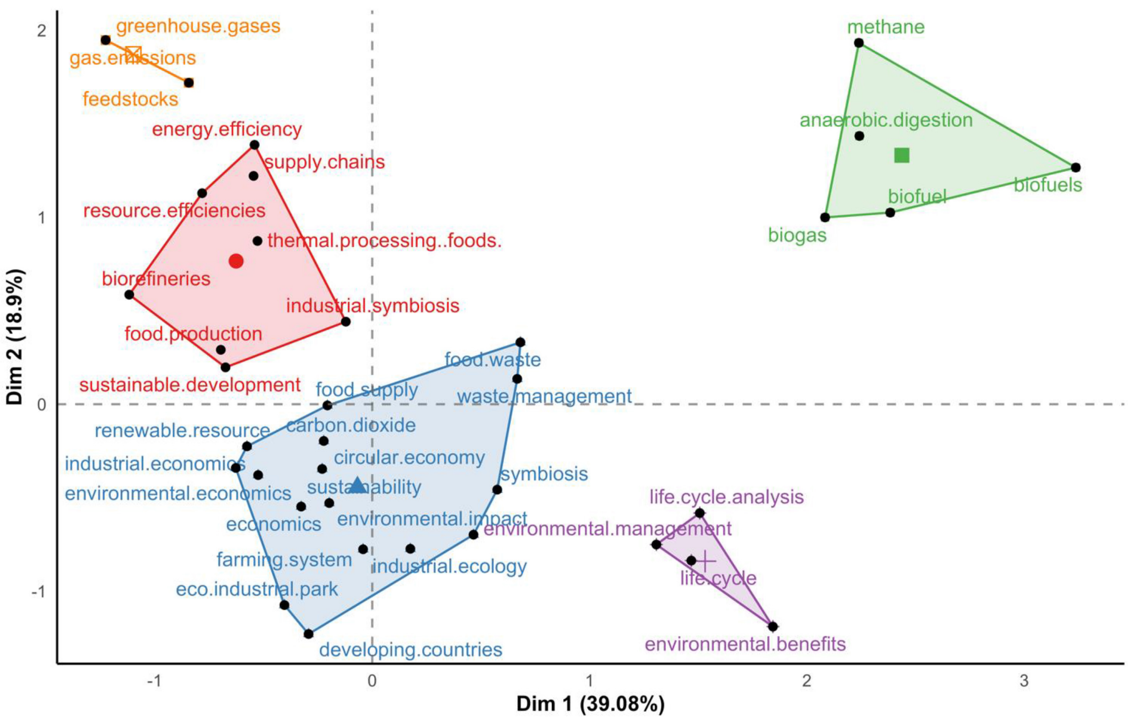


FIGURE 6
Multiple correspondence analysis. Source: our elaboration using "bibliometrix" R package.

5. Discussion

The previously presented research questions may be addressed by considering the results of the outcome analysis. It was considered feasible to pinpoint the primary emergent themes and their potential relationships using multiple correspondence analysis. As a result, the interpretation of the findings demonstrates that there are still extremely weak, if any, correlations between the methodologies used in the literature, and that the actual implementation of industrial symbiosis processes in the agri-food system is still a long way off.

10.3389/fsufs.2022.1012436

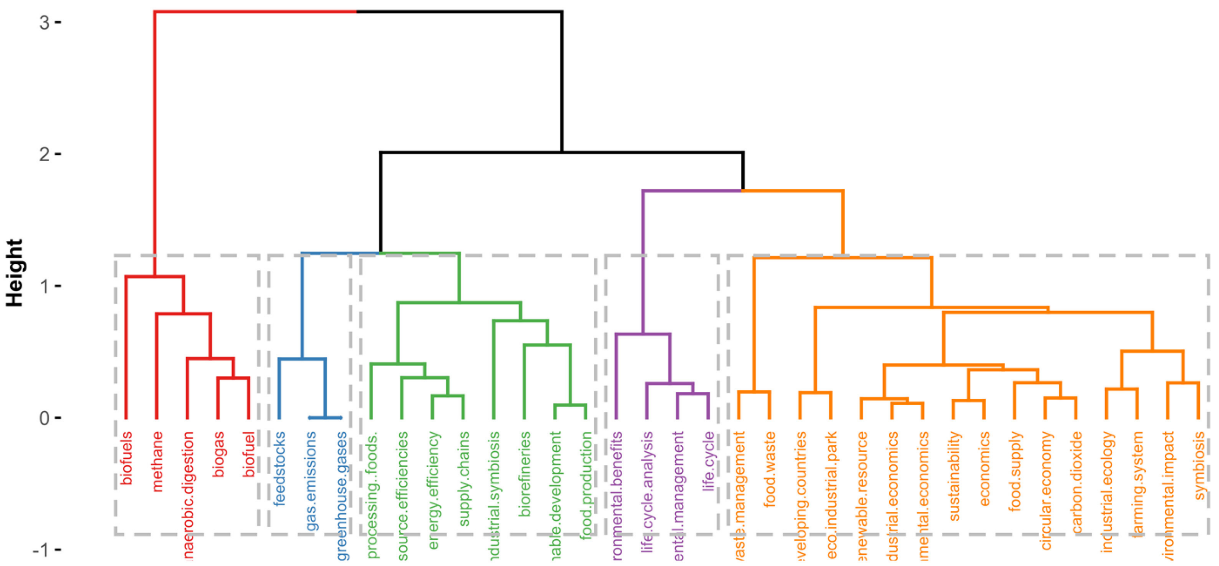


FIGURE 7
Dendrogram of hierarchical link between clusters. Source: our elaboration using "bibliometrix" R package.

A reading of the discovered clusters is provided hereafter.

5.1. Cluster 1: Food supply chain

The CE Action Plan supports the deployment of biotechnologies and practices to transform a range of value bio-based goods (Maina et al., 2017; Zabaniotou and Kamaterou, 2019).

In fact, the loss and waste of food along the agri-food chain is a critical economic, environmental, and social aspect that requires immediate legislative action (Teigiserova et al., 2020).

Adopting the idea of circular economy, which encompasses several closed-loop solutions, such as industrial symbiosis, is one of the measures that can be taken to avoid and control food loss and waste (Raimondo et al., 2018).

Examples of resource recovery within agri-food supply chains in the CE have emerged from among the analyzed studies (Do et al., 2021), with special reference to the valorisation of bioresidues from the brewing, dairy, slaughter, and forestry sectors (Gregg et al., 2020).

IS is suggested as a suitable technique for recovering by-products from catering and retail services, even in situations other than food production systems.

For instance, the research by Filimonau and Ermolaev (2022) suggested a model for food waste recovery in food services to investigate the potential of the industrial symbiosis of reducing food waste in food services in Russia. A favorable attitude was established, through interviews with food service providers and farmers, toward the industrial symbiosis model as a food waste recovery method and as a chance to build the social and network capital of food service providers and farmers.

In fact, food service providers acknowledged the ability of the model to optimize their operational expenses by decreasing the cost of solid waste collection and by supplying fresher and more affordable farm goods. The possibility of a cost reduction and the development of new food supply and processing chains also clearly and favorably affected the farmers' perception of the concept.

Food waste also occurs in the retail sector, due to the unpredictability of the consumers' demand.

In this respect, Lee and Tongarlak (2017) investigated how a symbiosis process could minimize food waste in a retail environment and how it interacts with other waste reduction measures, including the waste disposal cost and the food donation tax credit.

StunŽenas and Kliopova (2021) proposed an integrated food waste management model, based on the IE principle, which demonstrates that numerous prevention and technological solutions, such as dematerialisation and industrial symbiosis models, can be implemented to reduce environmental impacts, thereby enabling a management approach that is close to the natural one.

Alfaro and Miller (2014) applied IS principles to small farms in a region of West Africa, using optimisation techniques to maximize agricultural production and minimize waste, such as integrated farming, which views the farm as a system of new technologies that increases agricultural production and makes use of established IS tools to create alternative pathways, based on symbiotic relationships, to increase production.

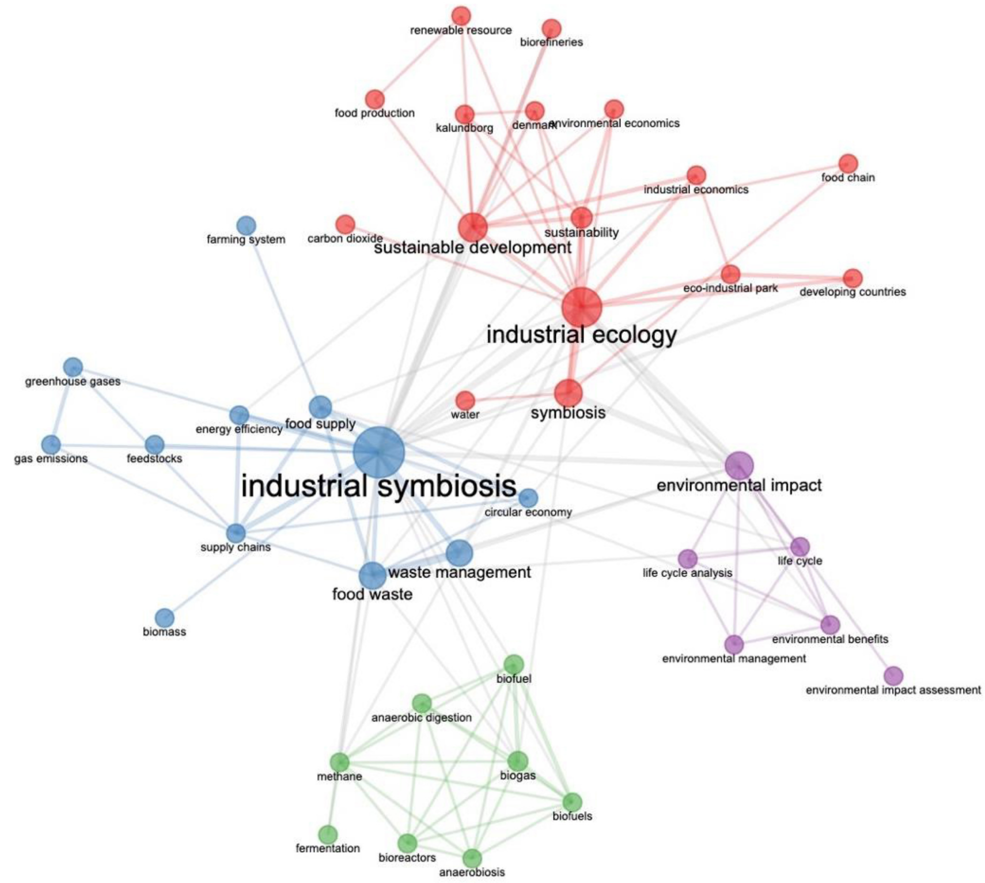


FIGURE 8
Co-occurrence network for keywords. Source: our elaboration using "bibliometrix" R package.

System integration of individual unit processes demonstrates increased productivity and decreased waste, thus indicating that there are still unrealised opportunities for IS in developing countries and that the integration of IS techniques into smallholder farming operations has the potential to influence sustainable development.

The cluster analysis revealed that the research is centered on a few specific cases and the agri-food sector as a whole. Moreover, there is a lack of research on certain industries, such the manufacturing of soft drinks or seafood, as opposed to wine or cereal.

Logistical concerns are other factors that have been overlooked in the research. For instance, there are few case studies that have dealt with the quantitative measurement of food waste generated by businesses. Another obstacle to the adoption of industrial symbiosis processes is the issue of geographical closeness to other businesses, which has not received enough attention in the literature.

5.2. Cluster 2: Life cycle assessment

Life cycle assessment (LCA) has been used extensively to measure the environmental benefits and costs of industrial symbiosis networks. Seven of the mentioned case studies evaluated the potential advantages of establishing industrial symbiosis processes using LCA as an analytical method.

For example, Kerdlap et al. (2020) introduced a methodology for modeling and analyzing the life-cycle environmental impacts of ISNs (Industrial Symbiosis Networks). This methodology enables models to be constructed that can be used to conduct multilevel assessments of the environmental performance of an individual or a set of waste-resource exchanges. An LCA was used to evaluate a prospective ISN for food waste-to-energy conversion in Singapore. The case study demonstrated that the technique is able to evaluate the environmental performance of a complete ISN.

Through a life cycle evaluation and a life cycle cost assessment, Diaz et al. (2021) investigated three major possible measures: energy recovery from waste *via* anaerobic digestion,

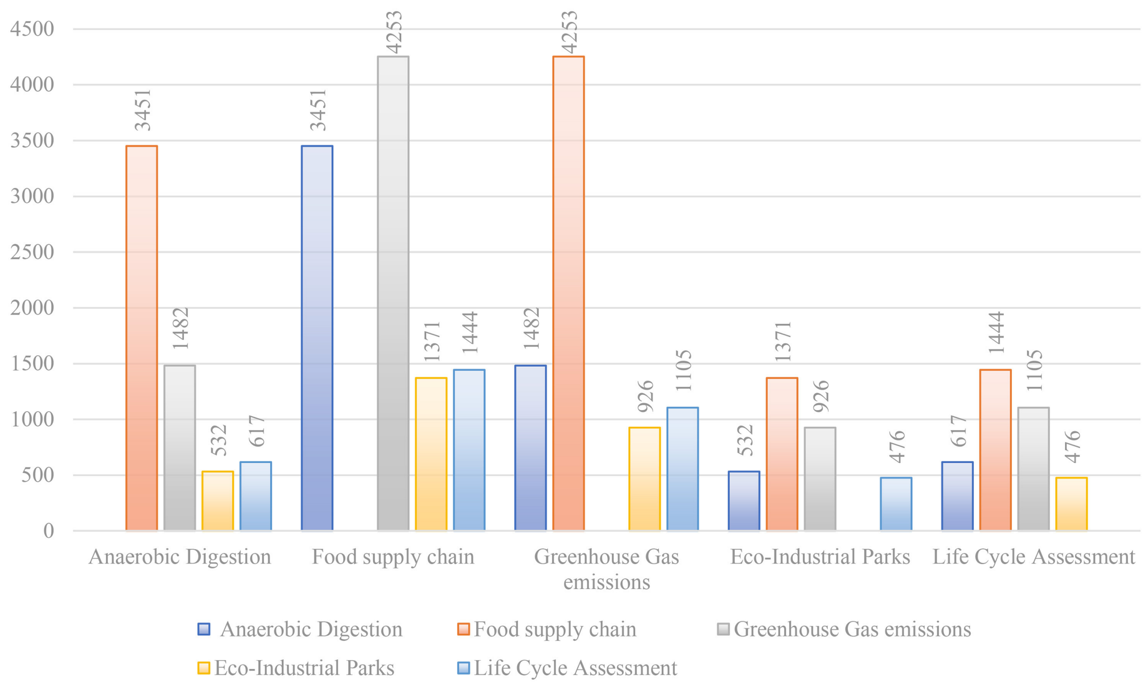


FIGURE 9
Co-occurrence network for clusters. Source: our elaboration using Wordstat.

the incorporation of renewable energy sources in warehouses, and the replacement of auxiliary equipment at a store. They discovered that the recovery of energy from food waste by means of anaerobic digestion and cogeneration offers the greatest advantages to the supply chain. Using a traditional life-cycle cost analysis, they determined that energy generation, through the utilization of waste for anaerobic digestion, was the most economically viable alternative.

Bhambhani et al. (2022) analyzed the advantages and disadvantages of the LCSA (Life Cycle Sustainability Assessment) methodology when used to evaluate the sustainability of water sector resource recovery systems. They identified three aspects of the LCSA that could be modified to better serve resource recovery solutions: its damage-based framework, its treatment of economic and natural capital as interchangeable, and its lack of environmental thresholds and historical emissions in its environmental assessment methodology.

Strazza et al. (2015) investigated a possible new turbo-drying technique for the recovery of cruise ship food waste for use as aquaculture feeds. They investigated the potential advantages of substituting standard salmon feed formulas with food waste, produced and processed on board a ship, by means of a comparative life-cycle evaluation.

Simboli et al. (2015) examined the potential growth of EI-based techniques in an Italian agri-food industry. The empirical data they used demonstrated that it was feasible to execute effective solutions *via* material substitution, repair, and recycling, as well as through the use of collaborative tactics between agriculture and industrial firms in the region.

According to the cluster analysis, LCA is now the most popular technique used for evaluating the environmental performance of industrial symbiosis processes that turn food waste into energy. This technique, together with other tools that encourage symbiotic interaction, might aid a variety of stakeholders in implementing eco-efficient systems in businesses and in obtaining the evidence-based information required to measure success, which will in turn assist in shaping laws and regulations.

5.3. Cluster 3: Eco-Industrial parks

Industrial ecosystems, eco-industrial networks and eco-industrial parks have been identified as the physical expressions of industrial symbiosis (Horn and Proksch, 2022).

Eco-industrial parks, which are based on a "top-down" approach, since they are developed from regulatory initiatives, represent communities of manufacturing and service firms in close locational proximity that coordinate to exchange material and informational resources in order to reduce waste, optimize the use of raw materials and energy, and promote multidimensional sustainable relationships between firms and key actors (Winans et al., 2017). The same concept is applied to industrial symbiosis and eco-industrial networks, where it is extended to a larger geographical area, even of the size of a state/province or nation (Winans et al., 2017).

Through cooperation, the business community seeks a greater collective advantage than the sum of the individual gains each company would obtain if it optimized its performance alone (Erkman, 1997; Lowe, 1997).

Denmark's Kalundborg eco-park is one of the most well-known examples of industrial symbiosis (Garner and Keoleian, 1995). The first network of exchanges, the first of water resources and then also of commodities and energy, arose in this region in the 1960s with twelve enterprises who considered IS at the core of their operations. This industrial ecosystem was created without the use of any specialized planning tools, but rather through bilateral agreements among several local businesses.

Significant environmental and economic advantages emerged from this IS situation. In fact, 14 million euros, 635 thousand tons of carbon dioxide, 3.6 cubic meters of water, 100 gigawatt hours of electricity, and 87,000 tons of materials were saved (Ehrenfeld and Gertler, 1997). Since then, other occurrences of eco-industrial parks have been documented (Mirata, 2004; Roberts, 2004; Zhu et al., 2007; Park et al., 2008).

Most of the case studies analyzed in this article suggest and have evaluated industrial symbiosis models for the development of eco-industrial parks to assess their technical, environmental, social, and economic viability (Frone and Frone, 2017; Hu et al., 2020).

For instance, Genc et al. (2020) suggested a novel design strategy for eco-industrial parks that takes into consideration the possibility of waste exchanges among co-located companies to mitigate the detrimental effects of market and company dynamism.

Genc et al. (2019) presented two approaches to analyse the robustness, redundancy, connectedness, and cyclicity of eco-parks in a Turkish industrial zone and to assess any variations in network topologies regarding prospective industrial symbiosis implementations. They also envisaged the possible future co-location of businesses in the industrial zone to facilitate the establishment of an industrial symbiotic network. The findings demonstrate that the approach may be used to evaluate the robustness of an industrial network.

Chatterjee et al. (2021) were the first to examine the advantages of using layered systems to achieve IS goals. They used a vast dataset, obtained from hypothetical and real industrial water networks, to demonstrate that highly layered designs cut resource use by a substantial amount. The findings indicate that the nesting concept may be an effective quantitative design principle for IS.

In 2015, Puente et al. (2015) showed the potential of small and medium-sized firms, concentrated in industrial districts or parks in northern Spain, for systemic eco-innovation *via* industrial symbiosis techniques.

Sanyé-Mengual et al. (2018) conducted a transnational comparative review, between Europe and South America, of eight case studies to obtain a more precise theoretical viewpoint on the prospective deployment of rooftop greenhouses in business parks. They used the life cycle and geographic information system assessment technique to estimate both the potential and anticipated advantages of building rooftop greenhouses. They discovered that business parks are better than industrial parks as urban locations for such undertakings.

Helenius et al. (2020) proposed agro-ecological symbiosis (AES) as a strategy to reconfigure primary food production in agriculture, food processing, and food community development in order to achieve system-level sustainability. Through sustained and robust collaboration and a co-creative process with trans-disciplinary actors, including food producers and processors as well as policy actors, they designed a food system model, based on networks of AES, that has the potential of facilitating the development of place-based food systems which advance the sustainability agenda.

The research of Brehm and Layton (2021) focused on the metric of nestedness, which is an ecological approach that resorts to the placement of linkages between nodes in a network to maximize network cyclicity for a given number of links. This measure provides numerous benefits for the design and study of EINs (Eco-Industrial networks), including maturity independence, size normalization, and strong statistical documentation of ecological systems with a high degree of mutualism.

The application of nestedness to EINs has revealed a lower occurrence of nested structures and a greater degree of unpredictability than is generally seen for food waste. Industrial networks also exhibit a link between high nesting and internal cycles, thus indicating that the reuse of materials and energy in EINs may be enhanced as a result of nesting structures more deeply.

Hardy and Graedel (2002) applied the food web theory to nineteen eco-industrial parks and biosystems, both real and fictional. They discovered a linear relationship by connecting the number of industrial participants and the number of linkages between them.

Wright et al. (2009) examined the possibilities for greater inter-disciplinary cooperation by determining whether the quantitative analytic approaches used in community ecology research were also applicable in an industrial environment in Nova Scotia. Their findings demonstrated that these methods are also applicable for industrial ecology.

Some research has focused on the growth of eco-industrial parks in eastern nations. Yu et al. (2015), for instance, used the Rizhao Economic and Technological Development Area as a case study to introduce the industrial symbiosis development process, research the evolution of industrial symbiosis and eco-industrial park construction, and summarize the factors and characteristics of industrial symbiosis development in China.

In addition, Shi et al. (2010) conducted a case study of the Tianjin Economic-Technological Development Area that summarized the characteristics of eco-industrial parks in a developing nation and assessed the environmental advantages of major symbiotic exchanges.

On the other hand, Ong et al. (2021) provided an overview of the existing management practices of industrial solid waste and the usual obstacles to the construction of an eco-industrial park in Malaysia.

Case studies related to eco-industrial parks make up the bulk of the cluster content analysis. Apart from exemplary instances, most of them serve as templates for possible eco-industrial parks that may be used in industrial symbiosis processes; empirical cases, on the other hand, are still very infrequent. The body of literature on this subject currently shows certain gaps.

5.4. Cluster 4: Greenhouse gas emissions

Global fossil carbon emissions have grown dramatically since the turn of the century, and the European Union currently ranks third for global emissions (Boden et al., 2017).

In this perspective, these emissions comprise 24% of the global greenhouse gas emissions from the agriculture industry (IPCC, 2014). Recent IPCC findings indicate that maintaining global warming below 2°C may be achieved by reducing GHG emissions from several sectors, including the agricultural industry (IPCC, 2019).

Burg et al. (2021) conducted a regional investigation on the availability of manure as a feedstock for biogas plants and as a greenhouse heat source. In their research, they correlated the potential supply of waste heat from biogas derived from manure with the peak heat demand of the greenhouses.

In addition, they determined the area-based heating requirement of greenhouses for year-round tomato production and the possible heat supply from manure biogas.

Kikuchi et al. (2016) instead suggested an effective IS concept after conducting a thermodynamic study of energy fluxes in a sugar mill.

Martin et al. (2022), through a life cycle evaluation, quantified the environmental performance of synergies linked to energy integration and the circular use of materials in vertical farming systems of a fictitious urban farm situated in the basement of a residential building in Stockholm.

Sanyé-Mengual et al. (2018) discovered that business parks are better than industrial parks as urban locations for such undertakings. In addition, the deployment of insulated greenhouses on rooftops in Europe and South America led to high production values, CO_2 reductions, and food independence.

According to the literature study, linear industrial processes are emerging as the primary issue that is causing greenhouse gas emissions. Assessments have been conducted to quantify the emissions from the agri-food sector *via* several case studies. As previously mentioned, LCA is one of the main tools in this sector. However, it seems that little progress has been made in creating strategic models that can be used in manufacturing to cut down these emissions.

5.5. Cluster 5: Anaerobic digestion

Anaerobic digestion is an effective and eco-friendly waste treatment method (Capson-Tojo et al., 2016) that permits energy recovery and digestate recycling (Slorach et al., 2019; Zabaniotou and Kamaterou, 2019; Battista et al., 2020).

To address the special features of bio-based value chains, the establishment of new bio-based value chains would need collaboration across hitherto unconnected industries. Most of the traits are attributable to the primary production of biological resources in value chains. Such processes are often characterized by seasonality, decentralization, and underlying quality changes resulting from environmental variables (De Meyer et al., 2014; Ghosh, 2016). Because of the low density and tendency to decompose of biomass, its transportability is often hampered. The transformation of primary biomass has been anticipated to take place at a regional scale and to be characterized by several dissimilar characteristics (De Angelis et al., 2018).

However, primary biomass is excellent for industrial symbiosis, since the process can be done on a modest scale in any geographic region (Ingrao et al., 2018; Muradin et al., 2018).

Several research works have confirmed the advantages of setting up agro-industrial symbiosis networks (Santos and Magrini, 2018) and have offered decision support tools to find the most desirable inputs, processes, and outputs for biorefining (Tsakalova et al., 2015; Moncada and Aristizábal, 2016; Yu et al., 2017).

Teigiserova et al. (2019) suggested that the economics of scope, based on cascade production, are beneficial for small- and medium-sized and short-chain biorefineries whose productions depend on food waste. Moreover, large-scale biorefineries with significant transport distances and a lengthy value chain witness a decrease in the quality of raw materials and elevated transport emissions. Smaller facilities, on the other hand, have lower related transit costs and fewer infrastructure constraints for sorting, storage, and transport (Mak et al., 2020), while their output is accelerated to boost value addition (Banerjee et al., 2018; Barampouti et al., 2019).

Ometto et al. (2007) determined that the replacement of fossil fuels with bioalcohol in agricultural, animal, and food activities is advantageous in sugarcane agriculture to ensure economic returns, environmental quality, and higher social equality.

Sheppard et al. (2019) analyzed the challenges and potential associated with resource sharing between food sectors and biorefineries. The purpose of the case study was to determine and assess the resource efficiencies and economics of co-location between a coffee bean roasting enterprise and the biorefining of its downstream byproduct, i.e., discarded coffee grounds. The analysis demonstrated that there may be substantial advantages.

Zhang et al. (2021) investigated the potential advantages of adopting the industrial symbiosis strategy in agriculture and horticulture for a possible Eco-Industrial Park in Canada consisting of dairy farming, greenhouse vegetable cultivation, and mushroom cultivation. They considered the anaerobic digestion of dairy manure to create biogas and digestate.

An analysis of the literature has shown that anaerobic digestion processes now appear to be the most environmentally, socially, and economically beneficial means of converting waste into energy. Researchers, together with stakeholders, should make more efforts to develop new methods for the reuse of by-products.

5.6. Recommendation and future research

The purpose of this article has been to identify the main themes that emerged from a review of the literature and to identify the main barriers to promoting industrial symbiosis in order to encourage innovative policies and ways to support its development.

The analysis of obstacles and drivers in this study provides valuable information for the research community and for business decision makers on the importance of implementing IS systems.

Despite the exemplary cases of industrial symbiosis, it remains to be understood why progress in IS implementation has been so hesitant and gradual.

The results of the study by Domenech et al. (2019) reveal, for example, that IS exchanges continue to face a number of challenges in Europe, some of which are related to risk and uncertainty, while others are related to poor IS project commercial margins and transaction costs.

Therefore, better policies that foster collaborations and reduce transaction costs, for example, through the use of indicators, and encourage ambitious goals, such as trust, geographic proximity, and knowledge and information exchange, are essential to promote IS deployment and foster the development of large-scale initiatives.

The latter appears to be a particularly limiting component of industrial symbiosis operations.

Supply chain management pays little attention to knowledge concealment (Fang, 2017; Butt and Ahmad, 2019; Connelly et al., 2019; Pérez-Salazar et al., 2019).

The concealment of information limits the transmission and interchange of information held by internal and external stakeholders about the utility, origin, and availability of food waste by-products (Butt and Ahmad, 2019; Singh, 2019; Mangla et al., 2021).

In encouraging industrial symbiosis, some authors (Raabe et al., 2017; Low et al., 2018) have emphasized the need for collaborative platforms that provide the necessary information to support the physical exchange of by-products between companies.

Moreover, information management should be closely linked to information exchange. In fact, if organizations hide information related to top-down supply chain operations, supply chains could become vulnerable and isolated (Butt and Ahmad, 2019; Singh, 2019).

Hence, information exchange is a crucial aspect of supply chain management to promote organizational responsiveness and creativity, as well as to improve the ability of organizations to cope with unforeseen challenges (Timpanaro et al., 2012; Di Vita et al., 2015; Pandey et al., 2020).

Instead, what emerges from the literature review presented in this paper is that the case studies have addressed the application of potentially applicable methods and tools to an industrial symbiosis system, but have avoided the collaborative aspect between actors, due to a lack of communication between them. We believe that collaboration and information exchange systems among stakeholders is an aspect that still requires studying, and needs more attention as it is one of the main barriers to the introduction of symbiotic systems.

For this reason, we suggest that an analysis that looks at the system as a whole, and which succeeds in identifying the links between different areas of study, and in proposing tools for collaboration between stakeholders through the design of innovative communication platforms, would lead to a better understanding of what the entry and exit points between different companies could be, and thus improve the collaborative efficiency between different production sectors to establish closer relationships and enable the sustainability and development of industrial symbiosis processes (Dora, 2019).

6. Conclusion

This research contributes to the identification of the most widely used techniques for industrial symbiosis, and can thus help scholars and practitioners in the study and modeling of IS.

A content analysis was conducted to gather qualitative evidence from the literature. We ascertained that although interest seems to have increased in recent years, the number of publications is still rather modest. Emerging topics include food waste, life cycle assessment, eco-industrial parks, anaerobic digestion, and greenhouse gas emissions. Most research suggests industrial symbiosis models that can be used within eco-industrial parks.

However, to implement industrial symbiosis and create a circular economy, it is necessary to assess the connections between the production and consumption stages of the economic system. Since there is no link between emerging sectors and the capabilities associated with them, the results indicate that the hiding of information is a barrier that disconnects the system and slows down the spread of industrial symbiosis processes.

In this regard, we propose that the exchange of knowledge and information among stakeholders will help the development of industrial symbiosis processes and enable the most appropriate methods for converting a company's waste into secondary raw materials for other companies.

The application of this new business model can be a key industrial policy, as it creates significant economic and environmental benefits for the business system and the community as a whole through an increase in the overall competitiveness of local production systems and a reduction in pressure on ecosystem services.

7. Limitation

In spite of the aim of providing a comprehensive review and synthesis of the literature, it was not possible to conceptualize several issues as thoroughly as we would have wanted to.

The main limitations of this search stem from the methods that we used to identify relevant papers. By focusing on only English-language publications, it is likely that several key articles on this topic were overlooked. Moreover, since only research articles and reviews were considered to ensure the quality of the reviewed publications, it is possible that there are conferences, books, and/or public papers on IS that have not been reported.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MH: conceptualization, data curation, methodology, software, writing—original draft preparation, and writing—review and editing. DS: methodology, software, writing—original draft preparation, and writing—review and editing. MR and RZ: writing—original draft preparation and writing—review and editing. GD, GC, and JT: writing—original draft preparation and writing—review, editing, and supervision. MD'A: writing—review and editing, supervision, project administration, and funding acquisition. All authors contributed to the article and approved the submitted version.

Funding

This research was supported by the project PRIN DRASTIC Driving The Italian AgriFood System Into A Circular Economy Model, PRIN-MIUR (2017 JYRZFF) and funded by the Italian Ministry of Education, University and Research (MIUR); GRINS Foundation, Growing Resilient, Inclusive and Sustainable; National Research, Development and Innovation Office, Hungary, Grant—K 143370 Agricultural Climate Change Adaptation Behavior and Circular Economy.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abson, D. J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., et al. (2017). Leverage points for sustainability transformation. *Ambio* 46, 30–39. doi: 10.1007/s13280-016-0800-y

Alfaro, J., and Miller, S. (2014). Applying industrial symbiosis to smallholder farms: modeling a case study in Liberia, West Africa. *J. Ind. Ecol.* 18, 145–154. doi: 10.1111/jiec.12077

Allenby, B. R. (1996). A design for environment methodology for evaluating materials. *Environ. Qual. Manag.* 5, 69–84. doi: 10.1002/tqem.3310050409

Al-Thani, N. A., and Al-Ansari, T. (2021). Comparing the convergence and divergence within industrial ecology, circular economy, and the energy-water-food nexus based on resource management objectives. *Sustain. Prod. Consum.* 27, 1743–1761. doi: 10.1016/j.spc.2021.04.008

Aria, M., and Cuccurullo, C. (2017). bibliometrix: an R-tool for comprehensive science mapping analysis. *J. Informetr.* 11, 959–975. doi: 10.1016/j.joi.2017.08.007

Aschemann-Witzel, J., and Stangherlin, I. D. C. (2021). Upcycled by-product use in agri-food systems from a consumer perspective: a review of what we know, and what is missing. *Technol. Forecast. Soc. Change* 168, 120749. doi: 10.1016/j.techfore.2021.120749

Atanasovska, I., Choudhary, S., Koh, L., Ketikidis, P. H., and Solomon, A. (2022). Research gaps and future directions on social value stemming from circular economy practices in agri-food industrial parks: insights from a systematic literature review. *J. Clean. Prod.* 354, 131753. doi: 10.1016/j.jclepro.2022.131753

Ayres, R. U., and Ayres, L. W. (1996). *Industrial Ecology*. Cheltenham: Edward Elgar Publishing.

Baldassarre, B., Schepers, M., Bocken, N., Cuppen, E., Korevaar, G., and Calabretta, G. (2019). Industrial symbiosis: towards a design process for eco-industrial clusters by integrating circular economy and industrial ecology perspectives. *J. Clean. Prod.* 216, 446–460. doi: 10.1016/j.jclepro.2019.01.091

Banerjee, S., Ranganathan, V., Patti, A., and Arora, A. (2018). Valorisation of pineapple wastes for food and therapeutic applications. *Trends Food Sci. Technol.* 82, 60–70. doi: 10.1016/j.tifs.2018.09.024

Barampouti, E. M., Mai, S., Malamis, D., Moustakas, K., and Loizidou, M. (2019). Liquid biofuels from the organic fraction of municipal solid waste: a review. *Renew. Sustain. Energy Rev.* 110, 298–314. doi: 10.1016/j.rser.2019.04.005

Batagelj, V., and Cerinšek, M. (2013). On bibliographic networks. *Scientometrics* 96, 845–864. doi: 10.1007/s11192-012-0940-1

Battista, F., Frison, N., Pavan, P., Cavinato, C., Gottardo, M., Fatone, F., et al. (2020). Food wastes and sewage sludge as feedstock for an urban biorefinery producing biofuels and added-value bioproducts. *J. Chem. Technol. Biotechnol.* 95, 328–338. doi: 10.1002/jctb.6096

Beaulieu, L. (2015). *Circular Economy: A Critical Literature Review of Concepts*. Centre Interuniversitaire de Recherche sur le Cycle de vie des Produits, Procédés et Services. Montréal, QC.

Bellia, C., Bacarella, S., and Ingrassia, M. (2022). Interactions between street food and food safety topics in the scientific literature—a bibliometric analysis with science mapping. *Foods* 11, 789. doi: 10.3390/foods11060789

Bhambhani, A., van der Hoek, J. P., and Kapelan, Z. (2022). Life cycle sustainability assessment framework for water sector resource recovery solutions: strengths and weaknesses. *Resour. Conserv. Recycl.* 180, 106151. doi: 10.1016/j.resconrec.2021.106151

Blomsma, F., and Brennan, G. (2017). The emergence of circular economy: a new framing around prolonging resource productivity. *J. Ind. Ecol.* 21, 603–614. doi: 10.1111/jiec.12603

Boden, T. A., Marland, G., and Andres, R. J. (2017). *National CO2 Emissions From Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2014*. Tennessee: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy.

Boix, M., Montastruc, L., Azzaro-Pantel, C., and Domenech, S. (2015). Optimization methods applied to the design of eco-industrial parks: a literature review. *J. Clean. Prod.* 87, 303–317. doi: 10.1016/j.jclepro.2014.09.032

Borrello, M., Pascucci, S., and Cembalo, L. (2020). Three propositions to unify circular economy research: a review. *Sustainability* 12, 4069. doi: 10.3390/su12104069

Brehm, C., and Layton, A. (2021). Nestedness of eco-industrial networks: exploring linkage distribution to promote sustainable industrial growth. *J. Ind. Ecol.*25, 205–218. doi: 10.1111/jiec.13057

Burg, V., Golzar, F., Bowman, G., Hellweg, S., and Roshandel, R. (2021). Symbiosis opportunities between food and energy system: the potential of manure-based biogas as heating source for greenhouse production. *J. Ind. Ecol.* 25, 648–662. doi: 10.1111/jiec.13078

Butt, A. S., and Ahmad, A. B. (2019). Are there any antecedents of top-down knowledge hiding in firms? Evidence from the United Arab Emirates. *J. Knowl. Manag.* 23, 1605–1627. doi: 10.1108/JKM-04-2019-0204

Capson-Tojo, G., Rouez, M., Crest, M., Steyer, J. P., Delgenès, J. P., and Escudié, R. (2016). Food waste valorization via anaerobic processes: a review. *Rev. Environ. Sci. Biotechnol.* 15, 499–547. doi: 10.1007/s11157-016-9405-y

Cembalo, L., Borrello, M., De Luca, A. I., Giannoccaro, G., and D'Amico, M. (2020). Transitioning agri-food systems into circular economy trajectories. *Aestimum* 199–218. doi: 10.13128/aestim-8860

Chatterjee, A., Brehm, C., and Layton, A. (2021). Evaluating benefits of ecologically-inspired nested architectures for industrial symbiosis. *Resour. Conserv. Recycl.* 167, 105423. doi: 10.1016/j.resconrec.2021.105423

Chertow, M., Ashton, W., and Kuppalli, R. (2004). *The Industrial Symbiosis Research Symposium at Yale: Advancing the Study of Industry and Environment*. Yale School of the Environment Publications Series 23. New Haven, CT.

Chertow, M. R. (2000). Industrial symbiosis: literature and taxonomy. *Annu. Rev. Energy Environ.* 25, 313–337. doi: 10.1146/annurev.energy.25.1.313

Chertow, M. R. (2007). Uncovering industrial symbiosis. *J. Ind. Ecol.* 11, 11–30. doi: 10.1162/jiec.2007.1110

Connelly, C. E., Cerne, M., Dysvik, A., and Škerlavaj, M. (2019). Understanding knowledge hiding in organizations. *J. Organ. Behav.* 40, 779–782. doi: 10.1002/job.2407

De Angelis, R., Howard, M., and Miemczyk, J. (2018). Supply chain management and the circular economy: towards the circular supply chain. *Prod. Plan. Control.* 29, 425–437. doi: 10.1080/09537287.2018.14 49244

De Meyer, A., Cattrysse, D., Rasinmäki, J., and Van Orshoven, J. (2014). Methods to optimise the design and management of biomass-for-bioenergy supply chains: a review. *Renew. Sust. Energ. Rev.* 31, 657–670. doi: 10.1016/j.rser.2013. 12.036

Despeisse, M., Ball, P. D., Evans, S., and Levers, A. (2012). Industrial ecology at factory level–a conceptual model. *J. Clean. Prod.* 31, 30–39. doi: 10.1016/j.jclepro.2012.02.027

Di Vita, G., Pilato, M., Pecorino, B., Brun, F., and D'Amico, M. (2017). A review of the role of vegetal ecosystems in CO2 capture. *Sustainability* 9, 1840. doi: 10.3390/su9101840

Di Vita, G. D., Allegra, V., and Zarbà, A. S. (2015). Building scenarios: a qualitative approach to forecasting market developments for ornamental plants. *Int. J. Bus. Glob.* 15, 130–151. doi: 10.1504/IJBG.2015.071152

Diaz, F., Vignati, J. A., Marchi, B., Paoli, R., Zanoni, S., and Romagnoli, F. (2021). Effects of energy efficiency measures in the beef cold chain: a life cycle-based study. *Rigas Tehn. Univer. Zinatniskie Raksti* 25, 343–355. doi: 10.2478/rtuect-2021-0025

Do, Q., Ramudhin, A., Colicchia, C., Creazza, A., and Li, D. (2021). A systematic review of research on food loss and waste prevention and management for the circular economy. *Int. J. Prod. Econ.* 239, 108209. doi: 10.1016/j.ijpe.2021.108209

Domenech, T., Bleischwitz, R., Doranova, A., Panayotopoulos, D., and Roman, L. (2019). Mapping industrial symbiosis development in Europe_ typologies of networks, characteristics, performance and contribution to the circular economy. *Resour. Conserv. Recycl.* 141, 76–98. doi: 10.1016/j.resconrec.2018.09.016

Dora, M. (2019). Collaboration in a circular economy: learning from the farmers to reduce food waste. *J. Enterp. Inf. Manag.* 33, 769–789. doi: 10.1108/JEIM-02-2019-0062

Dubois, O. (2011). *The State of the World's Land and Water Resources for Food and Agriculture: Managing Systems at Risk*. Rome; Eathscan.

Dumont, B., Fortun-Lamothe, L., Jouven, M., Thomas, M., and Tichit, M. (2013). Prospects from agroecology and industrial ecology for animal production in the 21st century. *Animals* 7, 1028–1043. doi: 10.1017/S1751731112002418

Duque-Acevedo, M., Belmonte-Ureña, L. J., Plaza-Úbeda, J. A., and Camacho-Ferre, F. (2020). The management of agricultural waste biomass in the framework of circular economy and bioeconomy: an opportunity for greenhouse agriculture in Southeast Spain. *Agronomy* 10, 489. doi: 10.3390/agronomy10040489

Ehrenfeld, J., and Gertler, N. (1997). Industrial ecology in practice: the evolution of interdependence at Kalundborg. *J. Ind. Ecol.* 1, 67–79. doi: 10.1162/jiec.1997.1.1.67

Erkman, S. (1997). Industrial ecology: an historical view. *J. Clean. Prod* 5, 1–10. doi: 10.1016/S0959-6526(97)00003-6

European Commission (2020). *Un Nuovo Piano D'azione Per L'economia Circolare.* Per un'Europa più pulita e più competitiva, COM/2020/98 final. Bruxelles: European Commission.

Fang, Y. H. (2017). Coping with fear and guilt using mobile social networking applications: knowledge hiding, loafing, and sharing. *Telemat. Inform.* 34, 779–797. doi: 10.1016/j.tele.2017.03.002

Fernandez-Mena, H., Nesme, T., and Pellerin, S. (2016). Towards an agro-industrial ecology: a review of nutrient flow modelling and assessment tools in agro-food systems at the local scale. *Sci. Total Environ.* 543, 467–479. doi: 10.1016/j.scitotenv.2015.11.032

Filimonau, V., and Ermolaev, V. A. (2022). Exploring the potential of industrial symbiosis to recover food waste from the foodservice sector in Russia. *Sustain. Prod. Consum* 29, 467–478. doi: 10.1016/j.spc.2021.10.028

Fraccascia, L., Magno, M., and Albino, V. (2016). Business models for industrial symbiosis: a guide for firms. *Proc. Environ. Sci. Eng. Manag.* 3, 83–93.

Frone, D. F., and Frone, S. (2017). "Circular economy in Romania: an industrial synergy in the agri-food sector," in *Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development*. 17.

Frosch, R. A., and Gallopolus, N. (1989). Strategies for manufacturing. *Sci. Am.* 261, 94. doi: 10.1038/scientificamerican0989-144

Galanakis, C. M. (2012). Recovery of high added-value components from food wastes: conventional, emerging technologies and commercialized applications. *Trends Food Sci. Technol.* 26, 68–87. doi: 10.1016/j.tifs.2012.03.003

Garner, A., and Keoleian, G. A. (1995). *Industrial Ecology: An Introduction, University of Michigan*. Ann Arbor, MI: National Pollution Prevention Center for Higher Education.

Genc, O., Kurt, A., Yazan, D. M., and Erdis, E. (2020). Circular eco-industrial park design inspired by nature: an integrated non-linear optimization, location, and food web analysis. *J. Environ. Manage*. 270, 110866. doi: 10.1016/j.jenvman.2020.110866

Genc, O., van Capelleveen, G., Erdis, E., Yildiz, O., and Yazan, D. M. (2019). A socio-ecological approach to improve industrial zones towards eco-industrial parks. *J. Environ. Manage*. 250, 109507. doi: 10.1016/j.jenvman.2019.109507

Ghosh, S. K. (2016). Biomass & bio-waste supply chain sustainability for bio-energy and bio-fuel production. *Proc. Environ. Sci.* 31, 31–39. doi: 10.1016/j.proenv.2016.02.005

Graedel, T. E., and Allenby, B. R. (1995). *Industrial Ecology Prentice Hall.* Englewood Cliffs, NJ.

Graedel, T. E., and Allenby, B. R. (2003). *Industrial Ecology*. Upple Saddle River, NJ: Prentice Hall.

Grant, G. B., Seager, T. P., Massard, G., and Nies, L. (2010). Information and communication technology for industrial symbiosis. *J. Ind. Ecol.* 14, 740–753. doi: 10.1111/j.1530-9290.2010.00273.x

Gregg, J. S., Jürgens, J., Happel, M. K., Strøm-Andersen, N., Tanner, A. N., Bolwig, S., et al. (2020). Valorization of bio-residuals in the food and forestry sectors in support of a circular bioeconomy: a review. *J. Clean. Prod* 267, 122093. doi: 10.1016/j.jclepro.2020.122093

Haller, H., Fagerholm, A. S., Carlsson, P., Skoglund, W., van den Brink, P., Danielski, I., et al. (2022). Towards a resilient and resource-efficient local food system based on industrial symbiosis in härnösand: a Swedish case study. *Sustainability* 14, 2197. doi: 10.3390/su14042197

Hamam, M., Chinnici, G., Di Vita, G., Pappalardo, G., Pecorino, B., Maesano, G., et al. (2021). Circular economy models in agro-food systems: a review. *Sustainability* 13, 3453. doi: 10.3390/su13063453

Hamam, M., D'Amico, M., Zarbà, C., Chinnici, G., and Tóth, J. (2022). Eco-Innovations transition of agri-food enterprises into a circular economy. *Front. Sustain. Food. Syst*. 6, 845420. doi: 10.3389/fsufs.2022.845420

Hardy, C., and Graedel, T. E. (2002). Industrial ecosystems as food webs. *J. Ind. Ecol.* 6, 29–38. doi: 10.1162/108819802320971623

Helenius, J., Hagolani-Albov, S. E., and Koppelmäki, K. (2020). Co-creating agroecological symbioses (AES) for sustainable food system networks. *Front. Sustain. Food Syst.* 4, 588715. doi: 10.3389/fsufs.2020.588715

Herczeg, G., Akkerman, R., and Hauschild, M. Z. (2018). Supply chain collaboration in industrial symbiosis networks. *J. Clean. Prod.* 171, 1058–1067. doi: 10.1016/j.jclepro.2017.10.046

Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Benton, T. G., Bodirsky, B. L., et al. (2020). Innovation can accelerate the transition towards a sustainable food system. *Nat. Food* 1, 266–272. doi: 10.1038/s43016-020-0074-1

Hirschfeld, H. O. (1935). A connection between correlation and contingency. *Math. Proc. Camb. Philos. Soc.* 31, 520–524. doi: 10.1017/S0305004100013517

Horn, E., and Proksch, G. (2022). Symbiotic and regenerative sustainability frameworks: moving towards circular city implementation. *Front. Built Environ.* 7, 780478. doi: 10.3389/fbuil.2021.780478

Hu, W., Tian, J., Li, X., and Chen, L. (2020). Wastewater treatment system optimization with an industrial symbiosis model: a case study of a Chinese eco-industrial park. *J. Ind. Ecol.* 24, 1338–1351. doi: 10.1111/jiec.13020

Imbert, E. (2017). Food waste valorization options: opportunities from the bioeconomy. *Open Agric.* 2, 195–204. doi: 10.1515/opag-2017-0020

Ingrao, C., Faccilongo, N., Di Gioia, L., and Messineo, A. (2018). Food waste recovery into energy in a circular economy perspective: a comprehensive review of aspects related to plant operation and environmental assessment. *J. Clean. Prod.* 184, 869–892. doi: 10.1016/j.jclepro.2018.02.267

IPCC (2014). *Climate Change: Mitigation of Climate Change.* New York, NY: IPCC.

IPCC (2019). *Land is a Critical Resource, IPCC Report Says*. New York, NY: IPCC.

Kalmykova, Y., Sadagopan, M., and Rosado, L. (2018). Circular economy–from review of theories and practices to development of implementation tools. *Resour. Conserv. Recycl.* 135, 190–201. doi: 10.1016/j.resconrec.2017.10.034

Kastner, C. A., Lau, R., and Kraft, M. (2015). Quantitative tools for cultivating symbiosis in industrial parks; a literature review. *Appl. Energy* 155, 599–612. doi: 10.1016/j.apenergy.2015.05.037

Kerdlap, P., Low, J. S. C., and Ramakrishna, S. (2019). Zero waste manufacturing: a framework and review of technology, research, and implementation barriers for enabling a circular economy transition in Singapore. *Resour. Conserv. Recycl*. 151, 104438. doi: 10.1016/j.resconrec.2019.104438

Kerdlap, P., Low, J. S. C., Tan, D. Z. L., Yeo, Z., and Ramakrishna, S. (2020). M3-IS-LCA: a methodology for multi-level life cycle environmental performance evaluation of industrial symbiosis networks. *Resour. Conserv. Recycl*. 161, 104963. doi: 10.1016/j.resconrec.2020.104963

Kikuchi, Y., Kanematsu, Y., Ugo, M., Hamada, Y., and Okubo, T. (2016). Industrial symbiosis centered on a regional cogeneration power plant utilizing available local resources: a case study of Tanegashima. *J. Ind. Ecol*. 20, 276–288. doi: 10.1111/jiec.12347

Koppelmäki, K., Eerola, M., Albov, S., Kivelä, J., Helenius, J., Winquist, E., et al. (2016). "Palopuro agroecological symbiosis: a pilot case study on local sustainable food and farming (Finland)," in *Challenges for the New Rurality in a Changing World Proceedings from the 7th International Conference on Localized Agri-Food Systems 8-10 May 2016* (Stockholm: Södertörn University).

Koppelmäki, K., Parviainen, T., Virkkunen, E., Winquist, E., Schulte, R. P., and Helenius, J. (2019). Ecological intensification by integrating biogas production into nutrient cycling: modeling the case of agroecological symbiosis. *Agric. Syst.* 170, 39–48. doi: 10.1016/j.agsy.2018.12.007

Lee, D., and Tongarlak, M. H. (2017). Converting retail food waste into by-product. *Eur. J. Oper. Res.* 257, 944–956. doi: 10.1016/j.ejor.2016.08.022

Li, X. (2018). "Industrial ecology and industrial symbiosis-definitions and development histories," in *Industrial Ecology and Industry Symbiosis for Environmental Sustainability* (London: Cham). doi: 10.1007/978-3-319-67501-5_2

Lombardi, D. R., and Laybourn, P. (2012). Redefining industrial symbiosis: crossing academic–practitioner boundaries. *J. Ind. Ecol.* 16, 28–37. doi: 10.1111/j.1530-9290.2011.00444.x

Low, J. S. C., Tjandra, T. B., Yunus, F., Chung, S. Y., Tan, D. Z. L., Raabe, B., et al. (2018). A collaboration platform for enabling industrial symbiosis: application of the database engine for waste-to-resource matching. *Proc. CIRP* 69, 849–854. doi: 10.1016/j.procir.2017.11.075

Lowe, E. A. (1997). Creating by-product resource exchanges: strategies for eco-industrial parks *J. Clean. Prod*. 5, 57–65. doi: 10.1016/S0959-6526(97)00017-6

Maesano, G., Milani, M., Nicolosi, E., D'Amico, M., and Chinnici, G. (2022). A network analysis for environmental assessment in wine supply chain. *Agronomy* 12, 211. doi: 10.3390/agronomy12010211

Maina, S., Kachrimanidou, V., and Koutinas, A. (2017). From waste to bio-based products: a roadmap towards a circular and sustainable bioeconomy. *Curr. Opin. Green Sustain. Chem*. 8, 18–23. doi: 10.1016/j.cogsc.2017.07.007

Mak, T. M., Xiong, X., Tsang, D. C., Iris, K. M., and Poon, C. S. (2020). Sustainable food waste management towards circular bioeconomy: policy review, limitations and opportunities. *Bioresour. Technol.* 297, 122497. doi: 10.1016/j.biortech.2019.122497

Mangla, S. K., Börühan, G., Ersoy, P., Kazancoglu, Y., and Song, M. (2021). Impact of information hiding on circular food supply chains in business-to-business context. *J. Bus. Res.* 135, 1–18. doi: 10.1016/j.jbusres.2021.06.013

Mantese, G. C., and Amaral, D. C. (2018). Agent-based simulation to evaluate and categorize industrial symbiosis indicators. *J. Clean. Prod.* 186, 450–464. doi: 10.1016/j.jclepro.2018.03.142

Marchi, B., Zanoni, S., and Zavanella, L. E. (2017). Symbiosis between industrial systems, utilities and public service facilities for boosting energy and resource efficiency. *Energy Proc.* 128, 544–550. doi: 10.1016/j.egypro.2017.09.006

Martin, M., Weidner, T., and Gullstrom, C. (2022). Estimating the potential of building integration and regional synergies to improve the environmental performance of urban vertical farming. *Front. Sustain. Food Syst.* 6, 849304. doi: 10.3389/fsufs.2022.849304

Mirabella, N., Castellani, V., and Sala, S. (2014). Current options for the valorization of food manufacturing waste: a review *J. Clean. Prod.* 65, 28–41. doi: 10.1016/j.jclepro.2013.10.051

Mirata, M. (2004). Experiences from early stages of a national industrial symbiosis programme in the UK: determinants and coordination challenges. *J. Clean. Prod.* 12, 967–983. doi: 10.1016/j.jclepro.2004.02.031

Mirata, M., and Emtairah, T. (2005). Industrial symbiosis networks and the contribution to environmental innovation: the case of the landskrona industrial symbiosis programme. *J. Clean. Prod.* 13, 993–1002. doi: 10.1016/j.jclepro.2004.12.010

Mitsuhiro, M., and Yadohisa, H. (2015). Reduced k-means clustering with MCA in a low-dimensional space. *Comput. Stat.* 30, 463–475. doi: 10.1007/s00180-014-0544-8

Moncada, J., and Aristizábal, V. (2016). Design strategies for sustainable biorefineries. *Biochem. Eng. J.* 116, 122–134. doi: 10.1016/j.bej.2016.06.009

Mulrow, J. S., Derrible, S., Ashton, W. S., and Chopra, S. S. (2017). Industrial symbiosis at the facility scale. *J. Ind. Ecol.* 21, 559–571. doi: 10.1111/jiec.12592

Muradin, M., Joachimiak-Lechman, K., and Foltynowicz, Z. (2018). Evaluation of eco-efficiency of two alternative agricultural biogas plants. *Appl. Sci.* 8, 2083. doi: 10.3390/app8112083

Neves, A., Godina, R., Azevedo, S. G., and Matias, J. C. (2020). A comprehensive review of industrial symbiosis. *J. Clean. Prod.* 247, 119113. doi: 10.1016/j.jclepro.2019.119113

Nowak, B., Nesme, T., David, C., and Pellerin, S. (2015). Nutrient recycling in organic farming is related to diversity in farm types at the local level. *Agric. Ecosyst. Environ.* 204, 17–26. doi: 10.1016/j.agee.2015.02.010

Ometto, A. R., Ramos, P. A. R., and Lombardi, G. (2007). The benefits of a Brazilian agro-industrial symbiosis system and the strategies to make it happen. *J. Clean. Prod.* 15, 1253–1258. doi: 10.1016/j.jclepro.2006.07.021

Ong, J., Mahmood, N. Z., and Musa, S. N. (2021). Challenges to promoting eco-industry parks in Malaysia: a case study of rawang integrated industrial park. *J. Mater. Cycles Waste Manag.* 23, 1258–1269. doi: 10.1007/s10163-021-01199-3

Onu, P., and Mbohwa, C. (2021). Industry 4.0 opportunities in manufacturing SMEs: sustainability outlook. *Mater. Today* 44, 1925–1930. doi: 10.1016/j.matpr.2020.12.095

Pagotto, M., and Halog, A. (2016). Towards a circular economy in Australian agri-food industry: an application of input-output oriented approaches for analyzing resource efficiency and competitiveness potential. *J. Ind. Ecol.* 20, 1176–1186. doi: 10.1111/jiec.12373

Pandey, P., Valkenburg, G., Mamidipudi, A., and Bijker, W. (2020). Responsible research and innovation in the global south: agriculture, renewable energy and the pursuit of symmetry. *Sci. Technol. Soc.* 25, 215–222. doi: 10.1177/0971721820902961

Park, H. S., Rene, E. R., Choi, S. M., and Chiu, A. S. (2008). Strategies for sustainable development of industrial park in Ulsan, South Korea—from spontaneous evolution to systematic expansion of industrial symbiosis. *J. Environ. Manage.* 87, 1–13. doi: 10.1016/j.jenvman.2006.12.045

Parker, T., and Svantemark, M. (2019). Resilience by industrial symbiosis? A discussion on risk, opportunities and challenges for food production in the perspective of the food-energy-water nexus. *Sustain. Earth* 2, 1–16. doi: 10.1186/s42055-019-0016-7

Pérez-Salazar, M. D. R., Aguilar-Lasserre, A. A., Cedillo-Campos, M. G., Juárez-Martínez, U., and Posada-Gómez, R. (2019). Processes and measurement of knowledge management in supply chains: an integrative systematic literature review. *Int. J. Prod. Res.* 57, 2136–2159. doi: 10.1080/00207543.2018.1521530

Poponi, S., Arcese, G., Pacchera, F., and Martucci, O. (2022). Evaluating the transition to the circular economy in the agri-food sector: selection of indicators. *Resour. Conserv. Recycl.* 176, 105916. doi: 10.1016/j.resconrec.2021.105916

Prendeville, S., Cherim, E., and Bocken, N. (2018). Circular cities: mapping six cities in transition. *Environ. Innov. Soc. Transit.* 26, 171–194. doi: 10.1016/j.eist.2017.03.002

Prieto-Sandoval, V., Jaca, C., and Ormazabal, M. (2018). Towards a consensus on the circular economy. *J. Clean. Prod.* 179, 605–615. doi: 10.1016/j.jclepro.2017.12.224

Puente, M. R., Arozamena, E. R., and Evans, S. (2015). Industrial symbiosis opportunities for small and medium sized enterprises: preliminary study in the Besaya region (Cantabria, Northern Spain). *J. Clean. Prod.* 87, 357–374. doi: 10.1016/j.jclepro.2014.10.046

Raabe, B., Low, J. S. C., Juraschek, M., Herrmann, C., Tjandra, T. B., Ng, Y. T., et al. (2017). Collaboration platform for enabling industrial symbiosis: application of the by-product exchange network model. *Proc. CIRP* 61, 263–268. doi: 10.1016/j.procir.2016.11.225

Radhakrishnan, S., Erbis, S., Isaacs, J. A., and Kamarthi, S. (2017). Novel keyword co-occurrence network-based methods to foster systematic reviews of scientific literature. *PLoS ONE* 12, e0172778. doi: 10.1371/journal.pone.0172778

Raimbault, J., Broere, J., Somveille, M., Serna, J. M., Strombom, E., Moore, C., et al. (2020). A spatial agent based model for simulating and optimizing networked eco-industrial systems. *Resour. Conserv. Recycl.* 155, 104538. doi: 10.1016/j.resconrec.2019.104538

Raimondo, M., Caracciolo, F., Cembalo, L., Chinnici, G., Pecorino, B., and D'Amico, M. (2018). Making virtue out of necessity: managing the citrus waste supply chain for bioeconomy applications. *Sustainability* 10, 4821. doi: 10.3390/su10124821

Raimondo, M., Hamam, M., D'Amico, M., and Caracciolo, F. (2022). Plastic-free behavior of millennials: An application of the theory of planned behavior on drinking choices. *Waste Manage.* 138, 253–61. doi: 10.1016/j.wasman.2021.12.004

Roberts, B. H. (2004). The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: an Australian case study. *J. Clean. Prod.* 12, 997–1010. doi: 10.1016/j.jclepro.2004.02.037

Saavedra, Y. M., Iritani, D. R., Pavan, A. L., and Ometto, A. R. (2018). Theoretical contribution of industrial ecology to circular economy. *J. Clean. Prod.* 170, 1514–1522. doi: 10.1016/j.jclepro.2017.09.260

Santos, V. E. N., and Magrini, A. (2018). Biorefining and industrial symbiosis: a proposal for regional development in Brazil. *J. Clean. Prod.* 177, 19–33. doi: 10.1016/j.jclepro.2017.12.107

Sanyé-Mengual, E., Martinez-Blanco, J., Finkbeiner, M., Cerd,à, M., Camargo, M., Ometto, A. R., et al. (2018). Urban horticulture in retail parks: Environmental assessment of the potential implementation of rooftop greenhouses in European and South American cities. *J. Clean. Prod* 172, 3081–3091. doi: 10.1016/j.jclepro.2017.11.103

Sehnem, S., Vazquez-Brust, D., Pereira, S. C. F., and Campos, L. M. (2019). Circular economy: benefits, impacts and overlapping. *Supply Chain Manag.* 24, 784–804. doi: 10.1108/SCM-06-2018-0213

Senauer, B., and Venturini, L. (2005). The globalization of food systems: a conceptual framework and empirical patterns. *J. Food Agric. Environ.* 389, 197. doi: 10.22004/ag.econ.14304

Sheppard, P., Garcia-Garcia, G., Angelis-Dimakis, A., Campbell, G. M., and Rahimifard, S. (2019). Synergies in the co-location of food manufacturing and biorefining. *Food Bioprod. Process.* 117, 340–359. doi: 10.1016/j.fbp.2019.08.001

Shi, H., Chertow, M., and Song, Y. (2010). Developing country experience with eco-industrial parks: a case study of the Tianjin economic-technological development area in China. *J. Clean. Prod.* 18, 191–199. doi: 10.1016/j.jclepro.2009.10.002

Simboli, A., Taddeo, R., and Morgante, A. (2015). The potential of industrial ecology in agri-food clusters (AFCs): a case study based on valorisation of auxiliary materials. *Ecol. Econ.* 111, 65–75. doi: 10.1016/j.ecolecon.2015.01.005

Singh, S. K. (2019). Territoriality, task performance, and workplace deviance: empirical evidence on role of knowledge hiding. *J. Bus. Res.* 97, 10–19. doi: 10.1016/j.jbusres.2018.12.034

Slorach, P. C., Jeswani, H. K., Cuéllar-Franca, R., and Azapagic, A. (2019). Environmental sustainability of anaerobic digestion of household food waste. *J. Environ. Manage.* 236, 798–814. doi: 10.1016/j.jenvman.2019.02.001

Spina, D., Vindigni, G., Pecorino, B., Pappalardo, G., D'Amico, M., and Chinnici, G. (2021). Identifying themes and patterns on management of horticultural innovations with an automated text analysis. *Agronomy* 11, 1103. doi: 10.3390/agronomy11061103

Stillitano, T., Falcone, G., Iofrida, N., Spada, E., Gulisano, G., and De Luca, A. I. (2022). A customized multi-cycle model for measuring the sustainability of circular pathways in agri-food supply chains. *Sci. Total Environ.* 844, 157229. doi: 10.1016/j.scitotenv.2022.157229

Strazza, C., Magrassi, F., Gallo, M., and Del Borghi, A. (2015). Life cycle assessment from food to food: a case study of circular economy from cruise ships to aquaculture. *Sustain. Prod. Consum.* 2, 40–51. doi: 10.1016/j.spc.2015.06.004

StunŽenas, E., and Kliopova, I. (2021). Industrial ecology for optimal food waste management in a region. *Environ. Res. Eng.* 77, 7–24. doi: 10.5755/j01.erem.77.1.27605

Teigiserova, D. A., Hamelin, L., and Thomsen, M. (2019). Review of high-value food waste and food residues biorefineries with focus on unavoidable wastes from processing. *Resour. Conserv. Recycl.* 149, 413–426. doi: 10.1016/j.resconrec.2019.05.003

Teigiserova, D. A., Hamelin, L., and Thomsen, M. (2020). Towards transparent valorization of food surplus, waste and loss: clarifying definitions, food waste hierarchy, and role in the circular economy. *Sci. Total Environ.* 706, 136033. doi: 10.1016/j.scitotenv.2019.136033

Timpanaro, G., Di Vita, G., Foti, V. T., and Branca, F. (2012). Landraces in Sicilian peri-urban horticulture: a participatory approach to Brassica production system. *Acta Horticult.* 1005, 213–220. doi: 10.17660/ActaHortic.2013.1005.22

Toop, T. A., Ward, S., Oldfield, T., Hull, M., Kirby, M. E., and Theodorou, M. K. (2017). AgroCycle–developing a circular economy in agriculture. *Energy Proc.* 123, 76–80. doi: 10.1016/j.egypro.2017.07.269

Trokanas, N., Cecelja, F., and Raafat, T. (2014). Semantic input/output matching for waste processing in industrial symbiosis. *Comput. Chem. Eng.* 66, 259–268. doi: 10.1016/j.compchemeng.2014.02.010

Tsakalova, M., Lin, T. C., Yang, A., and Kokossis, A. C. (2015). A decision support environment for the high-throughput model-based screening and integration of biomass processing paths. *Ind. Crops Prod.* 75, 103–113. doi: 10.1016/j.indcrop.2015.05.035

Unay-Gailhard, I., and Bojnec, Š. (2016). Sustainable participation behaviour in agri-environmental measures. *J. Clean. Prod.* 138, 47–58. doi: 10.1016/j.jclepro.2015.09.003

Unay-Gailhard, I., and Bojnec, Š. (2019). The impact of green economy measures on rural employment: green jobs in farms. *J. Clean. Prod.* 208, 541–551. doi: 10.1016/j.jclepro.2018.10.160

Van Beers, D., Bossilkov, A., Corder, G., and Van Berkel, R. (2007). Industrial symbiosis in the Australian minerals industry: the cases of Kwinana and Gladstone. *J. Ind. Ecol.* 11, 55–72. doi: 10.1162/jiec.2007.1161

Van Capelleveen, G., Amrit, C., and Yazan, D. M. (2018). "A literature survey of information systems facilitating the identification of industrial symbiosis," in *From Science to Society*, eds B. Otjacques, P. Hitzelberger, S. Naumann, and V. Wohlgemuth (Cham: Springer), 155–169. doi: 10.1007/978-3-319-65687-8_14

Vindigni, G., Mosca, A., Bartoloni, T., and Spina, D. (2021). Shedding light on peri-urban ecosystem services using automated content analysis. *Sustainability* 13, 9182. doi: 10.3390/su13169182

Walmsley, T. G., Ong, B. H., Klemeš, J. J., Tan, R. R., and Varbanov, P. S. (2019). Circular integration of processes, industries, and economies. *Renew. Sustain. Energy Rev.* 107, 507–515. doi: 10.1016/j.rser.2019.03.039

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al. (2019). Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492. doi: 10.1016/S0140-6736(18)31788-4

Winans, K., Kendall, A., and Deng, H. (2017). The history and current applications of the circular economy concept. *Renew. Sustain. Energy Rev.* 68, 825–833. doi: 10.1016/j.rser.2016.09.123

Wolf, A., Eklund, M., and Söderström, M. (2007). Developing integration in a local industrial ecosystem–an explorative approach. *Bus. Strat. Environ.* 16, 442–455. doi: 10.1002/bse.485

Wright, R. A., Côté, R. P., Duffy, J., and Brazner, J. (2009). Diversity and connectance in an industrial context: the case of Burnside Industrial Park. *J. Ind. Ecol.* 13, 551–564. doi: 10.1111/j.1530-9290.2009.00141.x

Yenipazarli, A. (2019). Incentives for environmental research and development: consumer preferences, competitive pressure and emissions taxation. *Eur. J. Oper. Res.* 276, 757–769. doi: 10.1016/j.ejor.2019.01.037

Yeo, Z., Masi, D., Low, J. S. C., Ng, Y. T., Tan, P. S., and Barnes, S. (2019). Tools for promoting industrial symbiosis: a systematic review. *J. Ind. Ecol.* 23, 1087–1108. doi: 10.1111/jiec.12846

Yu, C., Davis, C., and Dijkema, G. P. (2014). Understanding the evolution of industrial symbiosis research: a bibliometric and network analysis (1997–2012). *J. Ind. Ecol.* 18, 280–293. doi: 10.1111/jiec.12073

Yu, F., Han, F., and Cui, Z. (2015). Evolution of industrial symbiosis in an eco-industrial park in China. *J. Clean. Prod.* 87, 339–347. doi: 10.1016/j.jclepro.2014.10.058

Yu, H., Román, E., and Solvang, W. D. (2017). "A value chain analysis for bioenergy production from biomass and biodegradable waste: a case study in northern Norway," in *Energy Systems and Environment*, ed I. P. Tsvetkov (London: IntechOpen), 183–206. doi: 10.5772/intechopen.72346

Zabaniotou, A., and Kamaterou, P. (2019). Food waste valorization advocating circular bioeconomy-A critical review of potentialities and perspectives of spent coffee grounds biorefinery. *J. Clean. Prod.* 211, 1553–1566. doi: 10.1016/j.jclepro.2018.11.230

Zabaniotou, A., Rovas, D., Libutti, A., and Monteleone, M. (2015). Boosting circular economy and closing the loop in agriculture: case study of a small-scale pyrolysis–biochar based system integrated in an olive farm in symbiosis with an olive mill. *Environ. Dev. Sustain.* 14, 22–36. doi: 10.1016/j.envdev.2014.12.002

Zhang, S., Wang, H., Bi, X., and Clift, R. (2021). Synthesis and assessment of a biogas-centred agricultural eco-industrial park in British Columbia. *J. Clean. Prod.* 321, 128767. doi: 10.1016/j.jclepro.2021.128767

Zhu, Q., Lowe, E. A., Wei, Y. A., and Barnes, D. (2007). Industrial symbiosis in China: a case study of the guitang group. *J. Ind. Ecol.* 11, 31–42. doi: 10.1162/jiec.2007.929

frontiers | Frontiers in Sustainable Food Systems

TYPE Correction
PUBLISHED 07 March 2023
DOI 10.3389/fsufs.2023.1144122

OPEN ACCESS

EDITED AND REVIEWED BY
Maria Pilar Bernal,
Center for Edaphology and Applied Biology of Segura (CSIC), Spain

*CORRESPONDENCE
Daniela Spina
danispina@gmail.com

SPECIALTY SECTION
This article was submitted to Waste Management in Agroecosystems, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 13 January 2023
ACCEPTED 21 February 2023
PUBLISHED 07 March 2023

CITATION
Hamam M, Spina D, Raimondo M, Di Vita G, Zanchini R, Chinnici G, Tóth J and D'Amico M (2023) Corrigendum: Industrial symbiosis and agri-food system: Themes, links, and relationships.
Front. Sustain. Food Syst. 7:1144122.
doi: 10.3389/fsufs.2023.1144122

Corrigendum: Industrial symbiosis and agri-food system: Themes, links, and relationships

Manal Hamam[1], Daniela Spina[1]*, Maria Raimondo[1], Giuseppe Di Vita[2], Raffaele Zanchini[2], Gaetano Chinnici[1], József Tóth[3,4] and Mario D'Amico[1]

[1]Department of Agriculture, Food and Environment, University of Catania, Catania, Italy, [2]Department of Agricultural, Forest and Food Sciences, University of Turin, Turin, Italy, [3]Department of Agricultural Economics, Corvinus University of Budapest, Budapest, Hungary, [4]Faculty of Economics, Socio-Human Sciences and Engineering, Sapientia Hungarian University of Transylvania, Cluj-Napoca, Romania

KEYWORDS

industrial symbiosis, industrial ecology, circular economy, agri-food, content analysis, MCA

A corrigendum on
Industrial symbiosis and agri-food system: Themes, links, and relationships

by Hamam, M., Spina, D., Raimondo, M., Di Vita, G., Zanchini, R., Chinnici, G., Tóth, J., and D'Amico, M. (2023). *Front. Sustain. Food Syst.* 6:1012436. doi: 10.3389/fsufs.2022.1012436

In the original article, there was a mistake in "Figure 1. Industrial ecology structure. Source: Chertow (2000)." as published. The image for Figure 2 was incorrectly used for Figure 1. The corrected Figure 1 appears below.

The authors apologize for this error and state that this does not change the scientific conclusions of the article in any way. The original article has been updated.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

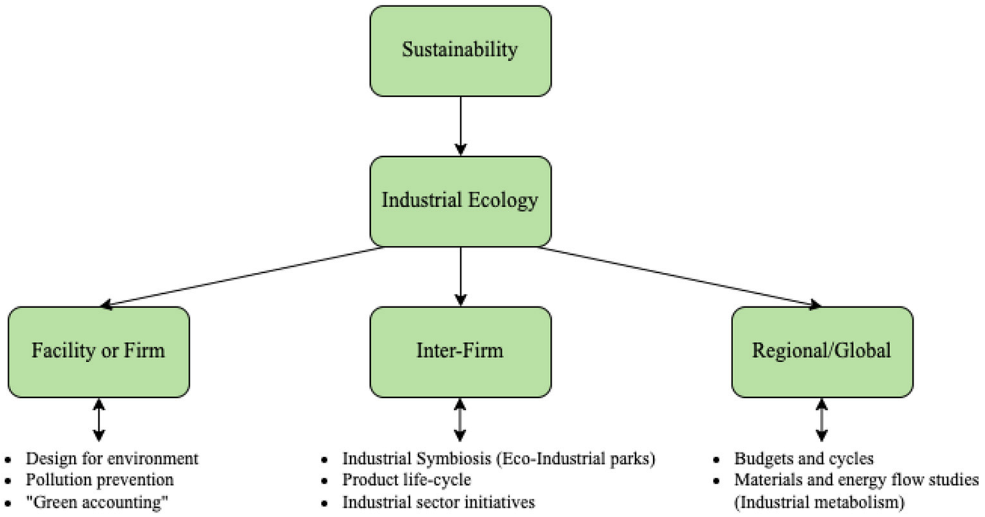


FIGURE 1
Industrial ecology structure. Source: Chertow (2000).

Reference

Chertow, M. R. (2000). Industrial symbiosis: literature and taxonomy. *Annu. Rev. Energy Environ.* 25, 313–337. doi: 10.1146/annurev.energy.25.1.313

TYPE Original Research
PUBLISHED 18 January 2023
DOI 10.3389/fsufs.2022.1028877

OPEN ACCESS

EDITED BY
Marzia Ingrassia,
Università degli Studi di Palermo, Italy

REVIEWED BY
Fabio Bartolini,
University of Ferrara, Italy
Astrida Miceikiene,
Vytautas Magnus University, Lithuania
Stelios Rozakis,
Technical University of Crete, Greece

*CORRESPONDENCE
Erika De Keyser
✉ erika.dekeyser@kuleuven.be

SPECIALTY SECTION
This article was submitted to Waste Management in Agroecosystems, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 26 August 2022
ACCEPTED 31 December 2022
PUBLISHED 18 January 2023

CITATION
De Keyser E and Mathijs E (2023) A typology of sustainable circular business models with applications in the bioeconomy. *Front. Sustain. Food Syst.* 6:1028877. doi: 10.3389/fsufs.2022.1028877

A typology of sustainable circular business models with applications in the bioeconomy

Erika De Keyser* and Erik Mathijs

Division of Bioeconomics, Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium

As an approach to sustainable development, circular business models are increasingly being developed. However, many circular business models focus on environmental or technological contributions to sustainability rather than considering all dimensions of sustainability simultaneously. Based on existing sustainable business model archetypes, a hierarchical business model typology is developed that allows a stepwise exploration of sustainable business model innovation opportunities incorporating an environmental, social and economic dimension. An analysis of business model components generates a closer look on the six newly defined Sustainable Circular Business Models. Finally, a conceptual application for organic waste valorization technologies, supported by examples from literature, allows a practical view on the implementation of the business models in the bio-economy. The typology offers a guide toward sustainable business model design or innovation opportunities centered around technologies creating value from waste.

KEYWORDS

business models, business model innovation, bioeconomy, circular economy, anaerobic digestion

1. Introduction

Following the definition of the 1987 Brundtland report, sustainable development is defined as “the development that meets the needs of the present without compromising the ability of future generations to meet their needs” (Brundtland, 1987). An early framework that aimed to translate this definition to a business setting is the Triple Bottom Line (TBL) framework. The TBL posits that instead of focusing on one bottom line, companies should commit to focusing on people, planet and profit. During the Johannesburg Summit in 2002, the term “profit” got replaced by “prosperity” to provide a more nuanced interpretation that also includes societal growth (United Nations, 2002). This reasoning is also present in Porter and Kramer (2011) definition of shared value creation, who argue that it is integral to profit maximization that businesses create economic value in a way that also creates societal value.

More recently, the importance of circularity has entered the debate on sustainable development (Geissdoerfer et al., 2017), particularly in reference to agricultural and food systems. More specifically, the Circular Economy (CE) is an umbrella term that has emerged from pre-existing concepts such as waste management and industrial symbiosis. Various definitions of the circular economy exist. The Ellen MacArthur Foundation (EMF), an influential non-governmental organization that has influenced the conceptual thinking behind the topic of the circular economy, defines the circular economy as “an economy that is restorative and regenerative by design and aims to keep products, components and materials at their highest utility and value at all times” (EMF, 2015). Despite the recent burst in academic literature, the concept is not new. Pioneering author Walter Stahel described his vision of an economy in loops in 1981 (Stahel and Reday-Mulvey, 1981). McDonough and Braungart (2002) further endorsed Walter Stahel’s philosophy by institutionalizing the term “cradle-to-cradle” as a sustainable alternative to the conventional “cradle-to-grave” approach.

CE principles distinguish between technical cycles involving non-renewable abiotic resources that cannot return to the biosphere, and biological cycles involving renewable biotic resources that can cycle in the biosphere (EMF, 2019; Navare et al., 2021). Biotic resources can return to the biosphere as nutrients nourishing ecosystems. In agricultural systems, for example, bio-based fertilizers can represent a circular alternative to the current chemical fertilizers (Chojnacka et al., 2020).

The transition to a CE does not only require innovative products and global networks, but also the development of new business models. Business model innovation is a key requirement for industry transformation related to the CE as well as sustainability (Geissdoerfer et al., 2017). Dantas et al. (2021) argue that a CE approach is very valuable to reach Sustainable Development Goals as it connects innovative technologies with new business models. The concept of the business model (BM) became popular with the rise of the Internet in the mid-1990's, when existing ways of earning a profit appeared unfitting for web-based products and services and a whole new range of opportunities for organizing business activities became available (Zott et al., 2011; DaSilva and Trkman, 2014). Meanwhile, the business model terminology has become widespread across all industries. Dozens of definitions have been proposed where scholars have mainly highlighted the notion of value, financial aspects and the network between the firm and its stakeholders (Amit and Zott, 2001; Chesbrough and Rosenbloom, 2002; Morris et al., 2005). A well-known tool to describe business models by their components is the Business Model Canvas by Osterwalder and Pigneur (2010). They distinguish 9 building blocks of a business model: the value proposition, customer segments, customer relationships, channels, key partners, key activities, key resources, cost structures and revenue streams. Baden-Fuller and Morgan (2010) use the analogy of recipes to describe the function of a BM: recipes require ingredients, but BMs cannot just be defined as the set of elements they contain because that would ignore the fact that they function as recipes to draw the elements together.

Applied to the CE, Salvador et al. (2020) define Circular Business Models (CBMs) as "[business models that] seek maintaining resource value at its maximum for as long as feasible, and eliminating or reducing resource leakage, by closing, slowing, or narrowing resource flows". Reim et al. (2019) define a CBM as "one in which a focal company, together with partners, uses innovation to create, capture, and deliver value to improve resource efficiency by extending the lifespan of products and parts that thereby realizes environmental, social, and economic benefits". Several taxonomies and typologies for CBM exist (Bocken, N. M. P. et al., 2016; Urbinati et al., 2017).

CBMs are often considered to be a subcategory of sustainable business models (Antikainen and Valkokari, 2016; Geissdoerfer et al., 2017). In addition to the circular economy, other concepts within the sustainability domain are for example the green economy and the bio-economy, although they all contain elements from each other (D'Amato et al., 2019). However, it is often emphasized that there is an imperfect overlap between sustainable business models and circular business models (Geissdoerfer et al., 2018). For example, CBMs can induce negative consequences for the working conditions of employees (social impact) or they can involve higher material and energy usages than their linear alternatives (environmental impact). There are many reasons why circular business model adoption may not contribute to sustainability (Whalen, 2019), such as the possibility of rebound effects (Zink and Geyer, 2017). Therefore, circular business models are not necessarily sustainable.

A literature review by Geissdoerfer et al. (2017) reveals that, considering a sustainable CE, most authors focus on the environmental performance improvements rather than taking a holistic view on all dimensions of sustainability. Social responsibility receives less attention in the circular economy (Murray et al., 2015). The synergies between the triple bottom line, the CE and sustainable business models should be further researched (Khan et al., 2021). A sustainable circular business model includes a holistic view on all dimensions of sustainability. A clear typology of sustainable circular business models (SCBM) is missing. In this study, a holistic SCBM is defined as a business model that aims to keep products, components and materials at their highest utility and value and thereby realizes environmental, social and economic benefits.

Boons and Lüdeke-Freund (2013) identify three streams of sustainable business model innovation: (1) technological innovation to overcome barriers of clean technologies, (2) organizational innovation and (3) social innovation to maximize social profit. However, these streams of innovation do not stand for separate phenomena: they are interlinked. They stress that an innovation bears a sustainability potential, but the business model is the market device that allows to unfold this potential. Bocken et al. (2014) build on these streams of innovation to identify 8 sustainable business model archetypes, representing groups of innovative business models sharing similar traits (Figure 1). Despite being originally developed for the manufacturing industry, the archetypes are also suitable for other sectors such as the agricultural sector (Barth et al., 2021). Nevertheless, as already pointed out by Bocken et al. (2014), a business model can be sustainable on a technological, social and organizational level simultaneously. Therefore, it is useful to adjust this typology to include a decomposition into subsystems and arrive at more holistic sustainable business models.

As the butterfly diagram of the Ellen MacArthur Foundation illustrates, the circular economy is not only relevant to technical systems, but also to biological cycles (EMF, 2019). Thus, CBMs are not only useful to describe businesses in the manufacturing sector, but they can also be useful to describe, for example, agri-food businesses or businesses in the bio-economy. For instance, an established technology for bio-based energy and fertilizer production is anaerobic digestion, a process in which biodegradable material is broken down in an anaerobic environment while releasing biogas and digestate. The produced biogas can be used for energy or fuel, while the remaining digestate is a nutrient-rich substance that can be used as a fertilizer. Anaerobic digestion is a key technology in sustainably developing modern circular biowaste technologies (Jain et al., 2022). However, in order to fulfill its full potential in a circular bio-economy, anaerobic digestion plants will face several challenges, including the improvement of economic viability and life cycle impacts (Sherwood, 2020). Despite an increasing awareness of scholars (Donner et al., 2020; Dagevos and de Lauwere, 2021), holistic business model typologies in the bio-economy are still scarce.

Such holistic typologies reveal an uncomplicated overview of SCBMs and create categories for classification. A typology based on contributions to sustainability draws out the underlying technological, social and organizational dimensions of the business models. It offers insights to establish a foundation toward the development of new sustainable business models.

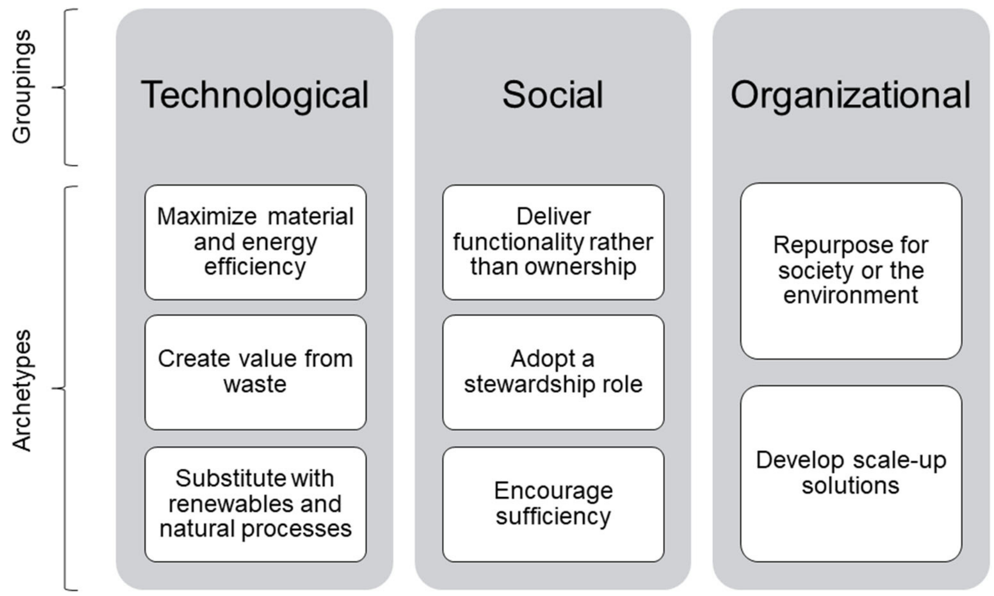


FIGURE 1
Sustainable business model archetypes adapted from Bocken et al. (2014).

The novelties compared to other business model typologies thus include the comprehensive and additive inclusion of multiple sustainability dimensions. This can be helpful for innovators who seek to develop business models for their technological innovations, as it provides guidance to include social and organizational innovations in their business model.

In order to develop such a holistic typology and show its applicability in the bio-economy, the research questions addressed in this paper are:

- What is a holistic typology for sustainable circular business models—and consequently, what are pathways for sustainable business model innovation?
- How can this typology be applied to the bio-economy, and more specifically, to anaerobic digestion as a source of technological innovation?

2. Conceptual framework

This paper aims to refine the sustainable business model archetypes developed by Bocken et al. (2014) to contribute to theory-building on the conceptualization of sustainable circular business models centered around technological innovations. Typologies are multidimensional and conceptual in their nature, but a good typology should be simple enough to allow a quick and easy comparison across types (Bailey, 1994). One way to model a complex system is to construct hierarchical structures and provide a decomposition in subsystems until the lowest level is reached (Simon, 1996). In this paper, the levels of innovation that distinguish the archetypes by Bocken et al. (2014) are interpreted hierarchically, allowing the development of a holistic typology.

2.1. Building a new typology

Starting from the sustainable business model archetypes as defined by Bocken et al. (2014), an adjusted categorization of sustainable business models can be derived by distinguishing three subsequent levels of innovation: (1) a technological level integrating the planet-dimension of the triple bottom line, (2) a social level integrating the people-dimension and an organizational level integrating the (3) prosperity-dimension (Figure 2). This is consistent with the definition of tri-profit by Upward and Jones (2015): a strongly sustainable business model should account for the sum of cost and revenues from activities in the environmental, social and economic context.

A first innovation level is the technological level: a circular innovation presenting solutions to achieve a sustainable future can focus on maximizing efficiency, creating value from waste or substituting materials or energy with renewables. Each technological innovation can be related to a stage of the "take-make-dispose" linear economy and presents a circular solution: substituting with renewables presents an alternative to the "taking"-stage by sourcing renewable inputs to design closed-loop systems. Maximizing efficiency brings a solution to the sustainability issues in the "making"-stage by narrowing resource loops. Creating value from waste brings a solution to the "dispose"-stage by closing resource loops (Bocken et al., 2014). These technological innovations are, however, not mutually exclusive: for example, a biogas digester can create value from biological waste while at the same time substituting fossil fuels with renewable energy from biogas. However, the business model typology should be regarded from the main aim of the business innovation. For example, if a biogas plant is established to convert crops that are grown with the sole purpose of turning them into biogas and fertilizer, the innovation aims at substituting with renewables. However, if a biogas plant is built to convert food waste from crops that have first gone through a consumption cycle, the innovation aims at creating value from waste.

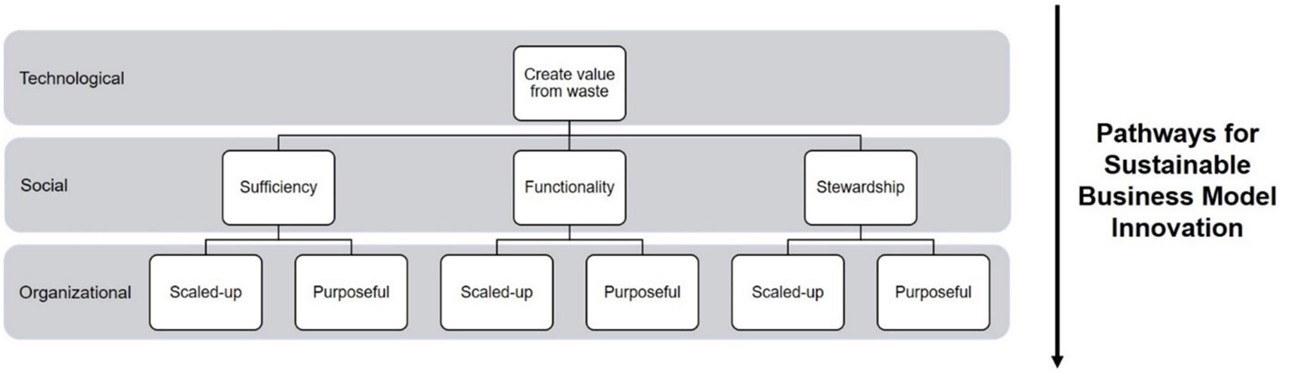


FIGURE 2
Hierarchical model providing a new typology of SCBMs.

Next, a business model adopting one of these technological innovations can provide social innovation. Social innovation, as defined by the European Commission (2013), indicates new ideas that meet social needs, create social relationships and form collaborations. This level of innovation can be looked at from the perspective of the provider of the technology and the value they create for their customers. The provider of a sustainable circular technology can either deliver functionality rather than ownership, adopt a stewardship role or encourage sufficiency. In all of these business models, social responsibility is not only emphasized by creating job opportunities but also by maintaining close social relationships within the supply network with a focus on trust and transparency. The social level is linked with the technological level through a part-whole relationship: the technological level represents an aggregation of different business model types on the social level. It can be noted that, in terms of circularity, the speed of the resource cycle can be impacted by the social level: by encouraging sufficiency, a firm can raise awareness about overconsumption (Bocken and Short, 2016). Firms that provide functionality have an incentive to prolong service life of products and may thus extend a product's life or use products more intensively to increase value to the firm (Tukker, 2015).

Finally, each business model can innovate organizationally by either repurposing its goals toward the delivery of social and environmental benefits rather than economic profit or scaling up sustainability solutions. A scaled-up sustainable business shows similarities to the definition of ecopreneurship by Schaltegger (2002) as these entrepreneurs focus on the mass market while being profit oriented and environmentally concerned at the same time. From a financial perspective, a company repurposing its goals will merely be focused on the survival of the company while a company scaling up its technology will aim for a stable income base. The organizational level forms a part-whole refinement of the social level by specifying whether or not the business model will be scale and profit oriented.

This hierarchy provides a new typology for SCBMs. A closer look allows to distinguish 6 SCBM archetypes for each technological innovation: purposeful functionality, scaled-up functionality, purposeful stewardship, scaled-up stewardship, purposeful sufficiency and scaled-up sufficiency. Based on the definitions of the sustainable business model archetypes by Bocken et al. (2014), the value propositions of these business models can be defined as follows:

- Scaled-up sufficiency is the reduction of demand-side consumption and hence production or the provision of high-quality durable products while scaling up sustainability solutions to maximize benefits for society and the environment;
- Purposeful sufficiency is the reduction of demand-side consumption and hence production or the provision of high-quality durable products while prioritizing the delivery of social and environmental benefits rather than economic profit;
- Scaled-up functionality is the provision of services that satisfy user needs without users having to own products while scaling up sustainability solutions to maximize benefits for society and the environment;
- Purposeful functionality is the provision of services that satisfy user needs without users having to own products, while prioritizing delivery of social and environmental benefits rather than economic profit;
- Scaled-up stewardship is the manufacturing and/or provision of products and/or services by considering the needs of a range of stakeholders and ensuring their long-term health and wellbeing, while scaling up sustainability solutions to maximize benefits for society and the environment;
- Purposeful stewardship is the manufacturing and/or provision of products and/or services by considering the needs of a range of stakeholders and ensuring their long-term health and wellbeing, while prioritizing the delivery of social and environmental benefits rather than economic profit.

2.2. Business model components

These newly defined business models can be further elaborated upon using business model elements as defined by the management literature. Morris et al. (2005) have synthetized the extant literature on business model into an integrative framework containing six components: (1) the value proposition, (2) the customer, (3) internal processes, (4) competencies, (5) competitive strategy and (6) entrepreneurial objectives, that are captured by six key questions. This section will address these components and link them to the definitions and descriptions of sustainable business model archetypes by Bocken et al. (2014), combined as described in 2.1. By answering the six questions for each newly defined business model separately, the framework allows for a clear distinction of business models in their fundamental characteristics. The standardization of decisions at the foundation level provides the opportunity to make comparisons across models. A summary is provided in Table 1.

2.2.1. How do we create value?

In business models offering functionality, such as product-service-systems (PSS), the provision of services is essential: consumer needs have to be satisfied, but this does not necessarily involve consumer ownership (Bocken et al., 2014; Tukker, 2015). In business models offering stewardship, both products and services can be offered; the value proposition is centered around the engagement of stakeholders (Bocken et al., 2014). Finally, in business models offering sufficiency, high-quality products that encourage long product life are offered. However, these products can be complemented with services inducing reduced consumption (Bocken and Short, 2016).

2.2.2. Who do we create value for?

This question relates to the organizational level of the business model: relational selling is about long-term relationships and getting to know customers' needs and wants while transactional relationships are about short-term sales (Payne, 1994). A distinction can be made between business models that re-purpose or scale-up. Business models that re-purpose the business for society and/or environment will focus on long-term relationships because they prioritize social and environmental benefits over shareholder value and integrate with local communities. Business models that scale-up their sustainability solutions, however, will place a bit more weight on the short-term sales so that their business is economically sustainable as well. However, this is not to say that scaled-up business models will not have any long-term relationships. For example, a firm offering stewardship, whether purposeful or scaled-up, will need long-term relationships with its stakeholders to ensure their health and wellbeing.

2.2.3. What is our source of competence?

This question relates to the value creation and delivery of the business model. Business models offering functionality rather than ownership may include redesign for durability, repairability and upgradability (Bocken et al., 2014). Those firms may have intellectual or technological capabilities that allow them to redesign their technology in such manner. Business models offering stewardship may need reconfiguration of their network to alternative suppliers who deliver benefits to their stakeholders (Bocken et al., 2014), indicating that these firms acquire significant networking and resource leveraging capabilities as well as great supply chain management. Business models encouraging sufficiency, on the other hand, are focused on consuming less, wasting less and using products longer (Bocken et al., 2014; Bocken and Short, 2016), indicating that a great source of competence is the production process. Finally, for scaled-up business models, selling and marketing will be an important asset to reach a large customer base.

2.2.4. How do we competitively position ourselves?

Purposeful business models require intimate relationships to discover the needs of the stakeholders. Scaled-up business models on the other hand, aim to capture economies of scale (Bocken, N. M. et al., 2016) and are thus more focused on low costs and efficiency. Business models offering functionality position themselves by offering exceptional services, while business models offering sufficiency focus on high-quality products. Business models offering stewardship, on the other hand, strive for operational excellence to fit the needs of their stakeholders. All business models discussed here position themselves by introducing a technological innovation meant to create value from waste, maximize efficiency or substitute with renewables.

2.2.5. How do we make money?

Business models offering functionality such as Product-Service-Systems (PSS) mostly have a fixed revenue source such as a monthly subscription. Their operations require a large amount of fixed costs including investment in the technology, which brings a high operating leverage. Business models offering stewardship can offer products and services while aiming to adjust their offerings to the specific situations of individual stakeholders (Bocken et al., 2014), providing flexible revenue sources. Since fixed costs can be shared among many stakeholders, operating leverage can be low. Business models offering sufficiency can have fixed revenue sources stemming from the sale of their products, while their investment costs of the technology and thus the operating leverage are high. Scaled-up business models aim to produce high volumes to scale up the technology and reach large numbers of people (Bocken, N. M. et al., 2016). While purposeful business models may aim to reach many people to maximize social and environmental benefits (Bocken et al., 2014), they do not aim to scale up production.

2.2.6. What are our time, scope and size ambitions?

Purposeful business models are focused on delivering social and environmental benefits instead of shareholder value (Bocken et al., 2014). For organizations driven by a social mission, the importance of growth diminishes (Johanisova and Wolf, 2012). Therefore, they will likely adopt a subsistence model where their goal is to survive and meet basic financial obligations. In some cases, they can employ an income model to generate a healthy income stream. Scaled-up business models will most likely employ such income model but may also aim for growth to the point that the firm generates capital gain for the initial investors.

3. Applications in the bio-economy

3.1. Methods

To show the applicability of this typology, representative examples from the bio-economy are provided. In the following paragraphs, the SCBM typology is applied to the bio-economy by elaborating on exemplar business models centered around anaerobic digestion (AD) of organic waste into energy as well as bio-based fertilizer. Anaerobic digestion is a well-established process to treat organic waste and produce renewable energy. Navare et al. (2021)

TABLE 1 SCBM's unraveled using the foundation level of the integrative framework by Morris et al. (2005).

	Purposeful sufficiency	Scaled-up sufficiency	Purposeful functionality	Scaled-up functionality	Purposeful stewardship	Scaled-up stewardship
How do we create value?	Primarily products	Primarily products	Primarily services	Primarily services	Mix of products and services	Mix of products and services
Who do we create value for?	Relational	Relational and transactional	Relational	Relational and transactional	Relational	Relational and transactional
What is our source of competence?	Production	Production Selling/marketing	Intellectual capability and technology	Intellectual capability and technology Selling/marketing	Networking/ resource leveraging Supply chain management	Networking/ resource leveraging Supply chain management Selling/marketing
How do we competitively position ourselves?	Intimate relationship Product quality Innovation	Product quality Innovation	Intimate relationship Service quality Innovation	Low cost and efficiency Service quality Innovation	Intimate relationship Operational excellence Innovation	Low cost and efficiency Operational excellence Innovation
How do we make money?	Fixed revenue source High operating leverage Low volumes	Fixed revenue source High operating leverage High volumes	Fixed revenue source High operating leverage Low volumes	Fixed revenue source High operating leverage High volumes	Mixed/flexible revenue sources Low operating leverage Low Volumes	Mixed/flexible revenue sources Low operating leverage High volumes
What are our time, scope and size ambitions?	Subsistence or income model	Income or growth model	Subsistence or income model	Income or growth model	Subsistence or income model	Income or growth model

stress that, in order to assess the circularity of biological cycles, four criteria should be monitored: cascading, sustainable harvesting, closing nutrient cycles and impacting resource depletion or carbon flows. Cascading, i.e., the sequential use of resources, involves a quality assessment and a consideration of the lifetime of a product to establish the highest value-added application (Bezama, 2016). In terms of cascading, high value organic residue applications include pharmaceuticals, food and feed and bioplastics. When these valorization options are ruled out, it can be interesting to produce lower value application such as bulk chemicals, fuels, energy and heat. Considering harvesting in residue-based biogas production, renewable energy is sourced from waste. Regarding nutrient recycling as a circular economy approach in the bio-economy, the use of organic waste could be a solution to recover valuable fertilizer components that could in time replace chemical fertilizers (Chojnacka et al., 2020) and thereby reduce resource depletion. As a pillar of the circular and bio-economy, this study focuses on anaerobic digestion. The analysis will focus on SCBMs in the bio-economy by describing exemplar business models centered around proprietors of anaerobic digesters, creating energy and digestate (i.e., a biobased fertilizer) from waste.

To find relevant literature, we used the following string to search the Web of Science database: TS = [(biogas OR anaerobic digest* OR (energy AND fertili*er)] AND (business model) AND (agri* OR farm*) in May 2022. Although the keyword "business model" delivers only a small part of literature related to anaerobic digestion applications, it represents the narrative part of business model literature. This was explicitly searched for, as it often provides a description of technological, organizational and social value propositions. This yielded 70 publications. Studies that did not go into detail on anaerobic digestion business models in the agri-food sector, were left out of consideration. Finally, 15 studies were considered to verify the SCBM typology with exemplary business models.

3.2. Sufficiency business models

Since fertilizers and other bio-based products will organically break down, the concept of "encouraging sufficiency" is ambiguous. In their research on sufficiency business strategies in the food industry, Bocken et al. (2020) suggest that sufficiency business models encourage the waste hierarchy of "avoid, reduce and reuse". As a method of avoiding overconsumption and reusing organic material, anaerobic digestion can reduce the need for externally produced goods (i.e., energy and fertilizer). As such, AD plants are considered sufficiency BMs if their value proposition intends to contribute to an increase in on-farm or regional energy or fertilizer self-sufficiency.

3.2.1. Purposeful sufficiency

In businesses providing purposeful sufficiency in circular fertilizers, the entrepreneurs aim to become self-sufficient in the sense of being capable to provide the most essential resources by themselves, without prioritizing profit maximization. Ximenes et al. (2021) analyze a case study of a company that anaerobically digests fish, oil and vegetable residues in the Northeast of Brazil. While a direct increase in profits may not be visible in the short term, the company will build energy independence and security as well as a positive brand image (Ximenes et al., 2021). The authors argue that the adoption of small-scale biogas and fertilizer production technologies can drive small agro-industrial companies and their sector to transform (Ximenes et al., 2021). Hamid and

Blanchard (2018) investigate the viability of small community biogas businesses in rural Kenya. This plant produces biogas for cooking and lighting for 5 households, while one farmer acts as the entrepreneur who installs and manages the plant. The authors suggest that community biogas entrepreneurship projects can meet domestic needs at a low cost while contributing to social development (Hamid and Blanchard, 2018). Karlsson (2019) describes farm-based biogas production in Sweden as a voluntary investment aimed to contribute to environmental and social sustainability while improving the farm's reputation and brand value and developing new value propositions. Most farmers find business efforts delivering environmental and social benefits more important than short-term profit maximization and aim to reduce consumption and production by improving product durability, reducing waste and reusing raw materials (Karlsson, 2019). Finally, Li et al. (2016) explore the promotion of rural biogas digesters in Qinhuangdao City, China. The city constructed more than 2,450 household digesters. This project was combined with the development of ecological organic agriculture by encouraging individuals to use the digestate as a fertilizer in ecological and organic agriculture. Households were trained about maintenance and use of digesters. The business model aims to solve air pollution problems with new energy and agricultural models in rural areas (Li et al., 2016).

Consistent with the purposeful sufficiency business model in Table 1, these examples have in common that they provide mainly products (i.e., biogas and digestate) for firm- or household-level sufficiency: the business models revolve around farm- or household-scale digesters producing energy and fertilizer to decrease their own dependency and contribute to rural development. Since social stakeholder value is prioritized, the entrepreneurs focus on long-term relationships rather than short-term sales. The provision of these products is not only motivated by cost savings but also by an intrinsic drive to get the most out of present resources. This involves an agroecological approach to crop production, allowing the farmer to align with the ecological specificities of their crops and soils. The farmer optimizes the production of both fertilizer and crops to create a responsible and resilient system for themself and the natural environment. Their source of competence is the production of energy and an innovative bio-based fertilizer. However, this requires a substantial investment. Whether or not the farmer produces low or high volumes at low or high margins, depends on the time and scope ambitions. For example, a farmer adopting a purposeful business model could solely aim to survive and continue its operations while maximizing social and environmental benefits (i.e., subsistence model). However, they could also aim to generate a stable base of cost savings (i.e., income model).

3.2.2. Scaled-up sufficiency

In scaled-up sufficiency business models, the entrepreneur will still aim to provide some essential resources themselves, but also aims to create a profit in doing so. The organizational priority thus changes to profit maximization in addition to social and environmental value creation. In Table 2, two scaled-up sufficiency case studies are described. We zoom in on the exploration of a pig breeding enterprise that has transitioned to a circular business to respond to challenges of low profitability by Zhu et al. (2019). The farm has improved pig production by offering green and organic high-quality pork, and has diversified income streams with bamboo, fish and electricity sales. At the same time, the farm saves on energy and fertilizers. Moreover, the farm is self-sufficient in its energy use, and additional energy is sold to the grid while additional fertilizer is provided to neighboring farms (Zhu et al., 2019). As such, the farm aims to increase revenue streams and save costs while achieving ecological and social goals. Environmental objectives are an integral part of the business (Zhu et al., 2019). Similarly, Sgroi et al. (2018) describe a case study of a biogas plant in Sicily, Italy. This company operates in the agro-energy sector, and more specifically, raises livestock and processes agricultural waste through anaerobic digestion. For this purpose, livestock waste is supplemented by energy crops. The farm saves on energy and fertilizer costs and generates an income through electricity sales to the grid and excess digestate sales to a supermarket chain. Sgroi et al. (2018) name the owner a "transforming entrepreneur" who manages a whole short chain as the farmer produces electricity (i.e., a side-product of his core business) as well as the raw materials. In addition, the authors argue that cost optimization and environmental sustainability go hand in hand in the search for energy self-sufficiency in agriculture, and that energy self-production increasingly becomes a source of competitive advantage.

In all three cases, the farmers prioritize profit maximization and an increase in revenue streams while reaching their self-sufficiency goals. They organize their business activities as described in the foundation level of scaled-up sufficiency models in Table 1. To allow the innovation to be effective in the long term, the farmer needs close relationships with their partners and customers. However, managing operations with different partners and customers implies that contractual agreements become important too. In addition to optimizing the production process, marketing skills are required to reach a large audience. The farmer aims to offer a qualitative and innovative product. Direct revenues might stem from fertilizer sales. Nevertheless, the profit generated by the innovation may also stem from cost-savings in mineral fertilizer use or even increased sale of other product lines. The farmer may choose to strive for a stable base of cost savings or income but may also hope to recover some capital in order to grow its business.

3.3. Functionality business models

Functionality business models revolve around the provision of services. In terms of anaerobic digestion, these can be waste conversion services as well as energy or fertilizer production services. As such, we assume that the end-users of these products are important customers of the central actor in this business model.

3.3.1. Purposeful functionality

In businesses providing purposeful functionality in circular fertilizers, the entrepreneurs aim to provide waste conversion, energy or fertilizer services with an innovative ownership value proposition, without prioritizing profit maximization. In Table 2, two examples of purposeful functionality are summarized. Liu et al. (2018) present a case study of bio-natural gas production in China by distinguishing multiple business models. In the "Mutual Offsetting in Kind" or product offsetting business model, farmers buy a share of the project's products (i.e., biogas and fertilizer) at a lower price in return for straw or manure. A similar business model is discussed by Ehsan et al. (2016). The authors design a biogas based chain business model

TABLE 2 Case studies and their technological, social and organizational value proposition.

	Case description	Country	Social priority	Organizational priority	References
Purposeful sufficiency	Small local agri- and aquaculture biogas model	Brazil (Ceará region)	Expanding the enterprise's offer of fish, prawns, lettuce and tomato by producing energy and fertilizer	Environmental commitment with society rather than source of economic benefits	Ximenes et al. (2021)
	Community biogas entrepreneurship	Kenya	Contributing to energy sufficiency of local households	Social and economic benefits to households	Hamid and Blanchard (2018)
	Farm-based biogas production	Sweden	Encouraging production and consumption sufficiency	Voluntarily benefiting environmental and social sustainability rather than profit maximization	Karlsson (2019)
	Household biogas digesters	China	Saving energy costs, reducing emissions and employing ecological and organic agricultural practices	Low-carbon rural community development	Li et al. (2016)
Scaled-up sufficiency	Pig breeding farm	China	Producing high-quality products, saving energy and fertilizer and contributing to regional circularity	Increasing profitability while achieving ecological and social goals	Zhu et al. (2019)
	Farm-based biogas plant	Italy (Sicily)	Transforming entrepreneurship targeting energy self-sufficiency	Source of supplementary income and competitive advantage that goes hand in hand with environmental sustainability	Sgroi et al. (2018)
Purposeful functionality	Product offsetting	China	Innovative ownership by farmers buying a quota of the project's products at a lower price in return for selling straw to the project	Supporting rural energy development and improvement of energy access	Liu et al. (2018)
	Biogas based chain business	Bangladesh	Purchasing waste from communities and offering them electricity, gas and fertilizer at an affordable price in return	Sustainable development of rural community	Ehsan et al. (2016)
Scaled-up functionality	Blockchain-based ecosystem	China	Innovative ownership by establishing an exchange system based on digital coupons	Contributing to environmental sustainability with financial incentives and a large quantity of transactions	Zhang (2019)
Purposeful stewardship	Support structure	Europe	Coordination, networking	Helping companies and sectors to develop	Donner et al. (2020)
	Contracted management	China	Professional assistance to farmers (*Nongbaomu*) and support of biogas and organic fertilizer production plants (*Negbaomu*)	Supporting rural energy development and improvement of energy access	Liu et al. (2018)
Scaled-up stewardship	Company X	UK	Collaboration and continuous dialogue, building trustworthy relationships with local stakeholders	SME recovering value from waste to provide clean energy as a competitive advantage	Hussain et al. (2020)
	Biovakka (origination)	Finland	Lowering the cost of disposing of excess manure for 20+ stakeholders (i.e., "coalition")	Profitability while solving the manure surplus problem in the region	Åkerman et al. (2020)
	A'Green Energy BM	USA	Majority farmer-owned business cooperation with food processing industry developing co-digestion AD projects	Increased profitability of dairy farmers and provision of renewable energy to the community	Morris et al. (2010)
	Sigma cooperative, biogas network	Sweden	Network-level business logic with focus on stakeholder collaboration and communication	Development of a business case for sustainability while increasing long-term financial profit and promoting the growth of the network	Karlsson et al. (2018, 2019)
Hybrid business models	Biogas plant	Europe	Local production, sale and usage of heat and electricity Provision of waste treatment services Collaboration and joint infrastructure development	Increased sales and revenue streams	Donner et al. (2020)

for a community in Bangladesh. There, households can sell various wastes to an authority in return for affordable biogas and bio-based fertilizers. This business model can reduce environmental and health hazards related to chemical fertilizer application and lower odor and waste pollution. The authors mention that this model is extendable to other rural communities and developed countries. While the goal is to achieve sustainable development in rural communities, the entrepreneurs can also achieve economic benefits in the long run (Ehsan et al., 2016).

These exemplary business models aim to promote the development of a rural economy and environmental governance through biogas production. In all cases, the entrepreneurs offer innovative ownership (e.g., a share of the products or a mutual exchange of goods) to the end-user. In doing so, they apply the principles as described by the foundation level of purposeful functionality models in Table 1. In both cases, the business model evolves around an authority that provides simultaneous waste conversion and energy and fertilizer production services to farmers or households. To be able to adapt their services to their customers, the companies need close and long-term relationships with the regional farmers. Running such a company requires sufficient intellectual capability and technologies. These innovative technologies in combination with high quality customer service and close relationships can put the company in an attractive position compared to competitors such as mainstream fertilizer producers.

3.3.2. Scaled-up functionality

In scaled-up functionality business models, the entrepreneur will still aim to provide innovative ownership to the end-customers, but also aims to create a profit in doing so. The organizational priority thus includes profit maximization as well as social and environmental value creation. In Table 2, a scaled-up sufficiency case study is described. Zhang (2019) discusses the Yitong system in China, collecting agricultural waste and converting them into energy and fertilizers. The authors suggests that this business model can be expanded with blockchain technology measuring the quantity of received waste, which is translated (e.g., with a coupon system) to an amount of energy and fertilizer that is owed to the waste-providing farms (Zhang, 2019).

While these businesses also provide innovative ownership, the difference with purposeful business models is that these companies will aim to profit from economies of scale. In this case, consistent with Table 1, the focus partially shifts from building close relationships with customers to increasing sales. The company will still need intellectual and technological capabilities in order to manage its operations fluently, but selling and marketing resources become important too in establishing a competitive position. Much like a purposeful functionality business model, this company will gain its competitive position from the service quality it delivers in offering innovative solutions. However, low costs and efficiency become principal characteristics in order to capture the economies of scale.

3.4. Stewardship business models

As a stewardship business model stresses the wellbeing of stakeholders, their key value proposition revolves around coordination and cooperation of technological operations. This is a broad interpretation of stewardship that allows for innovative collective ownership and organizational structures.

3.4.1. Purposeful stewardship

Businesses providing purposeful stewardship aim to coordinate a network of stakeholders without prioritizing profit maximization. Table 2 shows two exemplary business models. In the Nongbaomu or contracted agricultural management business model as discussed by Liu et al. (2018), farmers are assisted by professional personnel in soil preparation, harvesting, biomass collecting, bundling, storing and transporting. The farmers, however, keep ownership over their products. In the similar Nengbaomu or contracted energy management business model, biogas plants or fertilizer producers are supported (Liu et al., 2018). In a support structure as mentioned by Donner et al. (2020), circular activities are coordinated and brought together to help companies develop their circular business models. They can do this by providing coordination and support as well as joining efforts in waste valorization. The local niche cluster, organized by a leading association such as an NGO, consulting company, incubator, etc., brings together disconnected players. This way, they aim to maximize social benefits for its members while creating environmental value (Donner et al., 2020).

As indicated in Table 1, the entrepreneurs in these business models offer a mix of products and services, including support and know-how: knowledge and skills are shared. To ensure the long-term functioning of such support network or cooperative, close cooperation and transparent communication between farmers is needed. This implies a need for considerable networking and resource leveraging capabilities. As such, the business models take on cooperative, multi-partner and network structures. A centralized management of the flow of goods and services is important to secure trouble-free operations. In addition to intimate relationships with members or clients, the entrepreneurs will need to achieve operational excellence to manage the shared utilization of the innovation. Since the investment can be shared, operating leverage can be relatively low.

3.4.2. Scaled-up stewardship

In businesses providing scaled-up stewardship, the entrepreneurs aim to provide coordination and networking activities while making a profit. Table 2 provides four examples. For instance, Hussain et al. (2020) elaborates on a case company that operates a waste-to-energy AD plant with a specific aim of becoming circular. In their network of waste companies and food processing plants, expired food from retailers and bio-liquid from waste serve as process inputs. These close cooperative relationships have brought financial and operational benefits. The strategic location in between stakeholders does not only provide a logistic advantage, but is also beneficial to the local carbon footprint and quality of life. Collaboration is strengthened through knowledge sharing, joint research and investments. The company aims for economies of scale and scope by taking in more food waste and products. In their optimized and diversified process, they produce digestate, biogas and plastics from several biomass sources (Hussain et al., 2020). Åkerman et al. (2020) describes the case of Biovakka, founded by a coalition of pig farmers in Finland to solve the problem of regional manure surplus. This idea was based on collective centralized biogas plants as seen in Central Europe. While the main motivation of the business model was the recuperation of manure nutrients within the regional environmental constraints, the energy production provided a source of profits. Morris et al. (2010) elaborate on the business model of A Green Energy, a primarily farmer-owned business developing small-scale AD projects for on-farm co-digestion of manure and source-separated organics. Their value proposition centers around increasing profitability and providing renewable energy to the local community by establishing a cooperation between farmers and the food processing industry. Dairy farmers earn income from savings on energy usage, savings in fertilizer costs and sales of excess power to the local community. Additional revenue is made through contracts to accept food residuals from processing facilities (e.g., soup, seafood, or other products) at fees competitive to gate fees for landfill or composting. For processors, this cooperation increases sustainable procurement and credibility toward retailers (Morris et al., 2010). Finally, Karlsson et al. (2018, 2019) describe a Swedish farm cooperative with farm-based biogas production. In an attempt to solve their financial difficulties, the authors suggest moving toward a network-level business model in which farmers and stakeholders co-create value to establish a profitable plant that contributes to sustainable regional development. This collaborative business model relies on stakeholder relationships and the creation of a network in which risks and rewards are shared. Increased cooperation and novel partnerships drive improved marketing, sustainable brand creation and servitization (Karlsson et al., 2018, 2019).

In these business models, cooperative and network-structures can be recognized. However, the difference with purposeful business models is the focus on profits and economies of scale. Consistent with Table 1, transactional relationships become important as a larger installation or multiple input sources imply more managerial and practical agreements. On top of operational excellence in the provision of the innovation, low costs and efficiency become essential in order to capture economies of scale. To maximize their benefits, they will produce high volumes. They may aim for an income model that ensures a healthy income base, but they can also strive for growth opportunities that generate capital gain.

3.5. Hybrid business models

It should be noted that hybrid forms of these archetypes are possible. For example, a company can create value from waste while also maximizing efficiency or substituting with renewables. As mentioned previously in this paper, a biogas digester can create value from biological waste while at the same time substituting fossil fuels with renewable energy from biogas.

For example, Donner et al. (2020) describe a biogas plant as a key business model in the bio-economy (Table 2). The authors mention that both individual and collective infrastructures exist (Donner et al., 2020). Collective plants adopt stewardship characteristics by focusing on collaboration and joint infrastructure development. However, by locally producing, selling and using heat and electricity, a biogas plant can also adopt sufficiency characteristics. Finally, Donner et al. (2020) mention that farmers can – but do not necessarily have to – envisage waste treatment services as a source of income. In that case, the business model adopts a functionality value proposition.

As such, a business can create value in many ways simultaneously. However, the business model typology should be regarded from the main aim of the business innovation. Many businesses do not fit solely into one business model, but belong dominantly to one of them while they make use of elements of the others.

4. Discussion

By developing business model archetypes that incorporate sustainable innovations on a technological, social and organizational level, this paper aimed to distinguish pathways of sustainable business model innovation. To show its relevance, this typology was applied to 18 anaerobic digestion business models in the agri-food sector described by 15 papers in the literature search. The typology provides a part-whole overview of circular business models by focusing on three dimensions on sustainability.

Sufficiency anaerobic digestion business models, as suggested by this typology, are mostly farm- or household-scale digesters aiming to produce energy and fertilizer for (at least partial) self-consumption. While purposeful sufficiency business models focus on rural development, scaled-up sufficiency business models aim to diversify and increase revenues. Functionality anaerobic digestion business models focus on innovative ownership and service provision, either to encourage purposeful regional development or revenue diversification through a sustainable value proposition. Finally, stewardship anaerobic digestion models include cooperative, multi-partner and network business models. They can either be focused on sustainable regional or sectoral development, or network growth and long-term profit through economies of scale.

However, while the typology distinguishes a 3 fold sustainable value proposition within a circular business, the conceptualized SCBMs are not necessarily 100% sustainable. For example, a company adopting a business model that fits in the proposed typology by implementing a technological, social and organizational innovation does not necessarily treat its employees well and could still induce rebound effects. A good illustration is the business model of the Biovakka biogas installation in Finland, as described by Åkerman et al. (2020). This plant processed manure to improve its qualities as a fertilizer and produce energy. While this business model initially seemed a good approach to tackle the manure surplus, the business model was deemed unsustainable: since farmers were not interested in paying gate fees for manure, other feedstock had to be used, which lead to an increase in regional nutrient concentration worsening the surplus issue. The linkage to local pig farming became disconnected. The authors conclude that the regulatory framework was not in line with their ambitious goals. However, by integrating the sustainable business model archetypes by Bocken et al. (2014) in a stepwise approach, the business model will be one step closer to a holistic sustainable business model.

The application of a hierarchical model and the new typology of sustainable CBM contributes to the field of circular economy business models by proposing a new way to distinguish between sustainable CBM. It allows for a distinction of pathways to sustainable business model innovation that links innovative technologies to new business models by providing a clear storyline of how technological innovations can create, deliver and capture value in environmental, social and economic contexts. Therefore, a strength of this typology of sustainable business models is that it considers the three dimensions of the Triple Bottom Line. By defining three levels, the typology offers a stepwise exploration of sustainable business model innovation opportunities as a practical guide. Furthermore, the provision of examples in the bio-economy in this paper not only helps to clarify the categories defined by the newly introduced typology, but also brings a more realistic approach toward the implementation of the proposed business models.

While the applications in this paper focused on the technological archetype of "creating value from waste" as described by Bocken et al. (2014), the typology could also be relevant for the technological archetypes of "maximizing material and energy efficiency" and "substituting with renewables and natural processes". For example, Huijben and Verbong (2013) distinguish three types of photovoltaic (PV) business models that were experimented with in the Netherlands: customer-owned PV business models, community solar PV business models and third-party business models. In this typology, the distinction between sufficiency, stewardship and functionality can be recognized.

5. Conclusion

This study set out to develop a holistic typology for SCBMs based on existing sustainable business model archetypes. The research has identified and elaborated upon 6 newly defined archetypes of SCBMs. Furthermore, the applicability within the technological dimension of "creating value from waste" was shown by applying the typology to the production of bio-based fertilizers and energy *via* anaerobic digestion.

The business models as identified by this typology represent different approaches to a sustainable circular transformation. They are not mutually exclusive, and their application may be tailored to local needs and circumstances. The typology can inspire practitioners, including the government, on how to convert sustainability and circularity values into business cases. As such, it is useful to explore innovation opportunities for newly developed technologies, particularly on social and organizational levels.

Future work includes research on the relevance of this typology for other categories of sustainable business models such as zero carbon technologies or short supply chains. It is likely that this typology could be relevant for other sectors such as the energy sector. Similarly, the search for case studies to test the relevance of the identified business models typologies in other sectors can be useful. Additionally, among other factors, policies and incentives behind geographically varying case studies can differ. Further research on such barriers and drivers for different archetypes in the typology can guide policy makers in supporting the sustainable implementation of innovative circular solutions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ED: conceptualization, methodology, analysis, and writing—original draft. EM: conceptualization, methodology, review and editing, and supervision. Both authors contributed to the article and approved the submitted version.

Funding

This work was developed within and supported by the Horizon 2020-funded project RUSTICA under Grant Agreement No. 101000527.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Åkerman, M., Humalisto, N., and Pitzen, S. (2020). Material politics in the circular economy: The complicated journey from manure surplus to resource. *Geoforum* 116, 73–80. doi: 10.1016/j.geoforum.2020.07.013

Amit, R., and Zott, C. (2001). Value creation in E-business. *Strat. Manag. J.* 22, 493–520. doi: 10.1002/smj.187

Antikainen, M., and Valkokari, K. (2016). A framework for sustainable circular business model innovation. *Technol. Innov. Manag. Rev.* 6, 5–12. doi: 10.22215/timreview/1000

Baden-Fuller, C., and Morgan, M. S. (2010). Business models as models. *Long Range Plan.* 43, 156–171. doi: 10.1016/j.lrp.2010.02.005

Bailey, K. D. (1994). *Typologies and taxonomies: An introduction to classification techniques* (Sage University Paper series on Quantitative Applications in the Social Sciences, series no. 07-102). Thousand Oaks, CA: Sage. doi: 10.4135/9781412986397

Barth, H., Ulvenblad, P., Ulvenblad, P. O., and Hoveskog, M. (2021). Unpacking sustainable business models in the Swedish agricultural sector– the challenges of technological, social and organisational innovation. *J. Clean. Prod.* 304, 127004. doi: 10.1016/j.jclepro.2021.127004

Bezama, A. (2016). Let us discuss how cascading can help implement the circular economy and the bioeconomy strategies. *Waste Manag. Res.* 34, 593–594. doi: 10.1177/0734242X16657973

Bocken, N., Morales, L. S., and Lehner, M. (2020). Sufficiency business strategies in the food industry—the case of oatly. *Sustainability* 12, 824. doi: 10.3390/su12030824

Bocken, N. M., Fil, A., and Prabhu, J. (2016). Scaling up social businesses in developing markets. *J. Clean Prod.* 139, 295–308. doi: 10.1016/j.jclepro.2016.08.045

Bocken, N. M. P., de Pauw, I., Bakker, C., and van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *J. Indust. Prod. Engg*. 33, 308–320. doi: 10.1080/21681015.2016.1172124

Bocken, N. M. P., and Short, S. W. (2016). Towards a sufficiency-driven business model: Experiences and opportunities. *Environ. Innov. Soc. Transit.* 18, 41–61. doi: 10.1016/j.eist.2015.07.010

Bocken, N. M. P., Short, S. W., Rana, P., and Evans, S. (2014). A literature and practice review to develop sustainable business model archetypes. *J. Clean. Prod.* 65, 42–56. doi: 10.1016/j.jclepro.2013.11.039

Boons, F., and Lüdeke-Freund, F. (2013). Business models for sustainable innovation: state-of-the-art and steps towards a research agenda. *J. Clean. Prod.* 45, 9–19. doi: 10.1016/j.jclepro.2012.07.007

Brundtland, G. H. (1987). *Report of the World Commission on Environment and Development: Our Common Future* (United Nations General Assembly document A/42/427).

Chesbrough, H., and Rosenbloom, R. S. (2002). The role of the business model in capturing value from innovation: evidence from Xerox Corporation's technology spin-off companies. *Ind. Corpor. Change* 11, 529–555. doi: 10.1093/icc/11.3.529

Chojnacka, K., Moustakas, K., and Witek-Krowiak, A. (2020). Bio-based fertilizers: A practical approach towards circular economy. *Biores. Technol.* 295, 122223. doi: 10.1016/j.biortech.2019.122223

Dagevos, H., and de Lauwere, C. (2021). Circular Business Models and Circular Agriculture: Perceptions and Practices of Dutch Farmers. *Sustainability.* 13, 1282. doi: 10.3390/su13031282

D'Amato, D., Korhonen, J., and Toppinen, A. (2019). Circular, green, and bio Economy: How do companies in land-use intensive sectors align with sustainability concepts? *Ecol. Econ.* 158, 116–133. doi: 10.1016/j.ecolecon.2018.12.026

Dantas, T., de-Souza, E., Destro, I., Hammes, G., Rodriguez, C., and Soares, S. (2021). How the combination of Circular Economy and Industry 4.0 can contribute towards achieving the Sustainable Development Goals. *Sustain. Prod. Consumpt.* 26, 213–227. doi: 10.1016/j.spc.2020.10.005

DaSilva, C. M., and Trkman, P. (2014). Business model: What it is and what it is not. *Long Range Plan.* 47, 379–389. doi: 10.1016/j.lrp.2013.08.004

Donner, M., Gohier, R., and De Vries, H. (2020). A new circular business model typology for creating value from agro-waste. *Sci. Total Environ.* 716, 137065. doi: 10.1016/j.scitotenv.2020.137065

Ehsan, M. A., Das, C. K., and Hasan, M. (2016). "Biogas based chain business: A road to sustainable rural development," in *2016 4th International Conference on the Development in the in Renewable Energy Technology (ICDRET).* doi: 10.1109/ICDRET.2016.7421505

EMF (2015). *Growth within: a Circular Economy Vision for a Competitive Europe.*

EMF (2019). *Circular economy diagram.* Ellen MacArthur Foundation. Available online at: https://ellenmacarthurfoundation.org/circular-economy-diagram (accessed August 26, 2022).

European Commission (2013). *Social Innovation.* Internal Market, Industry, Entrepreneurship and SMEs. Available online at: https://ec.europa.eu/growth/industry/strategy/innovation/social_nl (accessed August 26, 2022).

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., and Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *J. Clean. Prod.* 143, 757–768. doi: 10.1016/j.jclepro.2016.12.048

Geissdoerfer, M., Vladimirova, D., and Evans, S. (2018). Sustainable business model innovation: A review. *J. Clean. Prod.* 198, 401–416. doi: 10.1016/j.jclepro.2018.06.240

Hamid, R., and Blanchard, R. (2018). An assessment of biogas as a domestic energy source in rural Kenya: Developing a sustainable business model. *Renew. Energy* 121, 368–376. doi: 10.1016/j.renene.2018.01.032

Huijben, J. C. C. M., and Verbong, G. P. J. (2013). Breakthrough without subsidies? PV business model experiments in the Netherlands. *Energy Policy* 56, 362–370. doi: 10.1016/j.enpol.2012.12.073

Hussain, Z., Mishra, J., and Vanacore, E. (2020). Waste to energy and circular economy: the case of anaerobic digestion. *J. Enter. Inf. Manage.* 33, 817–838. doi: 10.1108/JEIM-02-2019-0049

Jain, A., Sarsaiya, S., Kumar Awasthi, M., Singh, R., Rajput, R., Mishra, U. C., et al. (2022). Bioenergy and bio-products from bio-waste and its associated modern circular economy: Current research trends, challenges, and future outlooks. *Fuel* 307, 121859. doi: 10.1016/j.fuel.2021.121859

Johanisova, N., and Wolf, S. (2012). Economic democracy: A path for the future? *Futures* 44, 562–570. doi: 10.1016/j.futures.2012.03.017

Karlsson, N. P. (2019). Business models and business cases for financial sustainability: Insights on corporate sustainability in the Swedish farm-based biogas industry. *Sustain. Prod. Consumpt.* 18, 115–129. doi: 10.1016/j.spc.2019.01.005

Karlsson, N. P., Hoveskog, M., Halila, F., and Mattsson, M. (2018). Early phases of the business model innovation process for sustainability: Addressing the status quo of a Swedish biogas-producing farm cooperative. *J. Clean. Prod.* 172, 2759–2772. doi: 10.1016/j.jclepro.2017.11.136

Karlsson, N. P., Hoveskog, M., Halila, F., and Mattsson, M. (2019). Business modelling in farm-based biogas production: towards network-level business models and stakeholder business cases for sustainability. *Sustain. Sci.* 14, 1071–1090. doi: 10.1007/s11625-018-0584-z

Khan, I. S., Ahmad, M. O., and Majava, J. (2021). Industry 4.0 and sustainable development: A systematic mapping of triple bottom line, Circular Economy and Sustainable Business Models perspectives. *J. Clean. Prod.* 297, 126655. doi: 10.1016/j.jclepro.2021.126655

Li, G., Song, Y., and Jing, C. (2016). "Diversification development and utilization of new energy in rural areas - taking Qinhuangdao city of Hebei province as an example," in *Proceedings of the 2015 4th International Conference on Sustainable Energy and Environmental Engineering*. doi: 10.2991/icseee-15.2016.99

Liu, H., Ou, X., Yuan, J., and Yan, X. (2018). Experience of producing natural gas from corn straw in China. *Resour. Conser. Recycl.* 135, 216–224. doi: 10.1016/j.resconrec.2017.10.005

McDonough, W., and Braungart, M. (2002). *Cradle to Cradle: Remaking the Way We Make Things (1st ed.).* New York, NY: North Point Press.

Morris, C., Jorgenson, W., and Snellings, S. (2010). Carbon and energy life-cycle assessment for five agricultural anaerobic digesters in massachusetts on small dairy farms. *Int. Food Agribus. Manag. Rev.* 13, 1–8.

Morris, M., Schindehutte, M., and Allen, J. (2005). The entrepreneur's business model: toward a unified perspective. *J. Bus. Res.* 58, 726–735. doi: 10.1016/j.jbusres.2003.11.001

Murray, A., Skene, K., and Haynes, K. (2015). The circular economy: An interdisciplinary exploration of the concept and application in a global context. *J. Bus. Ethics* 140, 369–380. doi: 10.1007/s10551-015-2693-2

Navare, K., Muys, B., Vrancken, K. C., and Van Acker, K. (2021). Circular economy monitoring – How to make it apt for biological cycles? *Resour. Conserv. Recycl.* 170, 105563. doi: 10.1016/j.resconrec.2021.105563

Osterwalder, A., and Pigneur, Y. (2010). *Business Model Generation.* Hoboken, NJ, United States: Wiley.

Payne, A. (1994). Relationship marketing – Making the customer count. *Manag. Serv. Quality.* 4, 29–31. doi: 10.1108/EUM0000000003939

Porter, M., and Kramer, M. (2011). *Creating Shared Value.* Boston, MA, USA: FSG. Available online at: https://hbr.org/2011/01/the-big-idea-creating-shared-value (accessed August 26, 2022).

Reim, W., Parida, V., and Sjödin, D. R. (2019). Circular business models for the bioeconomy: A Review and new directions for future research. *Sustainability* 11, 2558. doi: 10.3390/su11092558

Salvador, R., Barros, M. V., Luz, L. M. D., Piekarski, C. M., and De Francisco, A. C. (2020). Circular business models: Current aspects that influence implementation and unaddressed subjects. *J. Clean. Prod.* 250, 119555. doi: 10.1016/j.jclepro.2019.119555

Schaltegger, S. (2002). A framework for ecopreneurship. *Greener Manage. Int.* 38, 45–58. doi: 10.9774/GLEAF.3062.2002.su.00006

Sgroi, F., Donia, E., and Alesi, D. R. (2018). Renewable energies, business models and local growth. *Land Use Policy* 72, 110–115. doi: 10.1016/j.landusepol.2017.12.028

Sherwood, J. (2020). The significance of biomass in a circular economy. *Biores. Technol.* 300, 122755. doi: 10.1016/j.biortech.2020.122755

Simon, H. A. (1996). *Sciences of the Artificial* (1st ed.). Cambridge, Massachusetts: The MIT Press

Stahel, W. R., and Reday-Mulvey, G. (1981). *Jobs for Tomorrow.* Amsterdam, Netherlands: Amsterdam University Press.

Tukker, A. (2015). Product services for a resource-efficient and circular economy – A review. *J. Clean. Prod.* 97, 76–91. doi: 10.1016/j.jclepro.2013.11.049

United Nations (2002). *Report of the World Summit on Sustainable Development* (A/CONF.199/20).

Upward, A., and Jones, P. (2015). An ontology for strongly sustainable business models. *Organiz. Environ.* 29, 97–123. doi: 10.1177/1086026615592933

Urbinati, A., Chiaroni, D., and Chiesa, V. (2017). Towards a new taxonomy of circular economy business models. *J. Clean. Prod.* 168, 487–498. doi: 10.1016/j.jclepro.2017.09.047

Whalen, K. A. (2019). Three circular business models that extend product value and their contribution to resource efficiency. *J. Clean. Prod.* 226, 1128–1137. doi: 10.1016/j.jclepro.2019.03.128

Ximenes, J., Siqueira, A., Kochańska, E., and Łukasik, R. M. (2021). Valorisation of agri- and aquaculture residues via biogas production for enhanced industrial application. *Energies* 14, 2519. doi: 10.3390/en14092519

Zhang, D. (2019). Application of blockchain technology in incentivizing efficient use of rural wastes: a case study on yitong system. *Energy Procedia* 158, 6707–6714. doi: 10.1016/j.egypro.2019.01.018

Zhu, Q., Jia, R., and Lin, X. (2019). Building sustainable circular agriculture in China: economic viability and entrepreneurship. *Manage. Decis.* 57, 1108–1122. doi: 10.1108/MD-06-2018-0639

Zink, T., and Geyer, R. (2017). Circular economy rebound. *J. Ind. Ecol.* 21, 593–602. doi: 10.1111/jiec.12545

Zott, C., Amit, R., and Massa, L. (2011). The business model: Recent developments and future Research. *J. Manage.* 37, 1019–1042. doi: 10.1177/0149206311406265

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 23 February 2023
DOI 10.3389/fsufs.2023.1092942

Check for updates

OPEN ACCESS

EDITED BY
Rachel Bezner Kerr,
Cornell University, United States

REVIEWED BY
Alfio Strano,
Mediterranea University of Reggio Calabria, Italy
Raffaella Pergamo,
Council for Agricultural and Economics Research (CREA), Italy

*CORRESPONDENCE
Alessandro Scuderi
✉ alessandro.scuderi@unict.it

SPECIALTY SECTION
This article was submitted to Water-Smart Food Production, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 08 November 2022
ACCEPTED 06 February 2023
PUBLISHED 23 February 2023

CITATION
Timpanaro G, Pecorino B, Chinnici G, Bellia C, Cammarata M, Cascone G and Scuderi A (2023) Exploring innovation adoption behavior for sustainable development of Mediterranean tree crops. *Front. Sustain. Food Syst.* 7:1092942. doi: 10.3389/fsufs.2023.1092942

Exploring innovation adoption behavior for sustainable development of Mediterranean tree crops

Giuseppe Timpanaro, Biagio Pecorino, Gaetano Chinnici, Claudio Bellia, Mariarita Cammarata, Giulio Cascone and Alessandro Scuderi*

Department of Agriculture, Food and Environment (Di3A), University of Catania, Catania, Italy

Introduction: The combination of knowledge, personal skills and company resources influences, all things being equal, such as the availability of new technologies, market conditions and other factors external to the company, farmers in their innovation choices. This study is an attempt to understand which psychological constructs influence the decision-making process of farmers specialized in typical Mediterranean crops with regard to innovation. Previous studies on the adoption of agricultural innovations have often considered socio economic characteristics and ignored the underlying motivational factors that influence the behavioral intention of farmers.

Methods: This study adopted three socio-psychological constructs, Attitude (ATT), Subjective Norm (SN), and Perceived Behavioral Control (PBC), derived from the Theory of Planned Behavior (TPB), and proposed three new constructs, Perceived Innovations Characteristics (PIC), Benefits (B), and Transferability (T), thus using an Extended Model of the Theory of Planned Behavior.

Results: The outcome of the multiple regression revealed that farmers' intention (I) to adopt sustainable irrigation innovations is positively influenced by attitude (ATT), subjective norm (SN), and perceived innovation characteristics (PIC). This last construct had mediating effects on the indirect relationships between PBC, benefits (B), transferability (T), and intention (I).

Discussion: The results provide numerous insights, useful both for outlining the demand for innovation and for calibrating future policies aimed at the primary sector, especially on the sustainable management of irrigation resources. In particular, the analyses carried out highlight the importance of factors external to the company as key levers in shaping the demand for innovations.

KEYWORDS

TPB, farm, economic, chain, water, climate change

1. Introduction

In a knowledge-based economy and with the acceleration of the globalization process that reduces the relevance of the spatial factor while accentuating the temporal factor to the extreme, the competitiveness of the territorial system increasingly depends on intangible resources (Capitanio et al., 2010), the capacity for interaction, collaboration and partnership (Rose and Chilvers, 2018; Kumar et al., 2021). Technology and innovation consequently acquire a strategic role in determining the competitive advantage of companies. In such a competitive environment, where innovation progressively takes the form of interaction between different companies or organizational units with complementary knowledge and skills (Guaitero et al., 2013; El Bilali, 2019), understanding the innovation process between different organizations becomes of great interest (Montes de Oca Munguia et al., 2021).

In economic theory, innovation is one of the key tools for a company's growth, entry into new markets and long-term sustainability (Sulistyo and Ayuni, 2020; Gutiérrez and Macken-Walsh, 2022; Ploll et al., 2022). Driven by increasing competition in global markets and unprecedented interest in sustainability practices, companies are seeking to implement more advanced sustainability practices (Hasler et al., 2016; Liu et al., 2018), seeking to maintain the high value of the products and services they provide through rapid and continuous innovation (Müller et al., 2018; Rabadán et al., 2019). However, companies often face the intention to innovate with uncertainty and concern, as they are confronted with a number of unfavorable factors, such as: lack of financial resources (Schaltegger and Wagner, 2011; Quintero et al., 2022), innovation costs that are too high, lack of qualified staff to manage innovations in the company, lack of knowledge of innovations, lack of confidence in innovations (Shi et al., 2022), low interest in innovations and long-term results (Sivertsson and Tell, 2015; Wang et al., 2022).

The agricultural sector faces significant challenges due to competing economic and environmental objectives. In this context, agricultural innovation can contribute to achieving higher production while preserving the environment (Läpple et al., 2015; Kubankova et al., 2016). Innovation in the agro-food industry, however, is lower than in other manufacturing sectors: according to recent studies, the agro-food sector, like the paper, printing and publishing, rubber and plastics sectors, invests around 2% of its turnover in R&D (Jun and Kim, 2022), while other sectors such as the chemical, electronic and mechanical sectors devote around 6–9% to this activity (Mekonnen et al., 2015).

The reasons for these low levels of expenditure compared to other sectors are to be found in the lack of basic research, the fact that innovation is exogenous and embedded in machinery, packaging and supplies in general (Coghlan et al., 2020; Fieldsend et al., 2022). Most of the innovations that have appeared in the agri-food sector do not originate from within the sector, but arise from the application and transfer of the results of research conducted in other areas, as was the case, for example, with the automation of processes, the control of results, especially in terms of quality (Curry et al., 2021; Bigliardi and Filippelli, 2022). Consequently, facilitating agricultural innovation is vital to the success of the agricultural sector. This has also been recognized by the EU with the creation of the European Innovation Partnership for Productivity and Sustainability (EIP-AGRI), which aims to foster sustainable and competitive agriculture as well as greater dissemination of innovations through increased links between research and agriculture (Barth et al., 2017; Feo et al., 2022a). Furthermore, it is widely recognized that continuous innovation is necessary in order to achieve sustainable agricultural development (Ploll et al., 2022; Takács-György and Takács, 2022).

Agricultural innovation is increasingly seen as a process involving the input of different actors and also as something that depends on the social structure of a specific context (Läpple et al., 2015; Feo et al., 2022b). It evolves as a result of interactions between different actors, such as farming systems, supply chains and economic systems (Klerkx et al., 2012), environmental policies, extension and social systems, reflecting the idea of Agricultural Innovation Systems (AIS) (Maru, 2018; Klerkx and Begemann, 2020). Among the different types of innovation in agriculture, a particularly important role today is played by those related to irrigation practices (Asadi et al., 2020). Today, in fact, water scarcity and droughts are a major problem (Saeed et al., 2021), probably exacerbated by climate change, which represents one of the greatest environmental, social and economic threats to the entire planet (Ungureanu et al., 2020; Ermolieva et al., 2022).

These needs also result from the fact that the agricultural system, as a result of the climatic changes we have been observing in recent years (Masia et al., 2018), has been affected by meteorological changes, which have led to earlier phenological phases of crops, a decrease in the availability of water in the soil and in the flow rates of watercourses, and low reservoir levels in natural and artificial reservoirs (Nguyen et al., 2016; Zagaria et al., 2021). These situations, over the years, have produced negative effects on the production level of many crops (Hashem et al., 2019), drawing attention to the rational use of water availability in agriculture (Kalinin et al., 2018; Zhang et al., 2022). In this scenario, irrigation can be used to offset the negative impacts of climate change on food supply, (Kukal and Irmak, 2018; Malek et al., 2018; Masia et al., 2018) but would require a 40–100% increase in water use for irrigation (Liu et al., 2017; Bafdal et al., 2018; Zaporozhchenko et al., 2022). In relation to this question, the question arises as to whether the public is willing to allocate such quantities of irrigation water for agriculture (Khandaker and Kotzen, 2018; de Oliveira Padilha et al., 2022), also in relation to the limited availability of water for domestic use and the alternatives set up by the food industry with food obtained in the laboratory or in hyper-intensive systems such as "Lab-grown meat" (van Loo et al., 2020; Galanakis et al., 2021) or as Vertical farming (Niu and Masabni, 2021; van Gerrewey et al., 2022).

Technology, innovation and Agriculture 4.0 are the solution today, as they can reduce water consumption in agriculture by up to 20 per cent compared to traditional irrigation systems (Adeyemi et al., 2017; Velasco-Muñoz et al., 2019; Kourgialas et al., 2022). In the fruit-growing world, the most economical systems are drip systems: micro-sprinklers (Canaj et al., 2021), underground drip sprinklers and mini-sprinklers (Loures et al., 2020; Rouzaneh et al., 2021). In the context of innovations, the Mediterranean tree crops sector is certainly one of those that has received less attention in the economic literature (Coghlan et al., 2020). Furthermore, it appears that the adoption of innovation has been studied mainly in large fruit companies in developed countries, while research on innovation in small companies has received little attention (Migliore et al., 2015; Kim et al., 2019). Small farms in the sector are, in fact, part of the agri-food system and play an important role in the economic growth of the country (Rajapathirana and Hui, 2018; Bigliardi and Filippelli, 2022).

In small business management, it is widely recognized in the literature (Aksoy, 2017; Barth et al., 2017) that the competence of entrepreneurs, farmers and professional managers plays an important role in the adoption of business innovation (Mozzato et al., 2018; Yan et al., 2022). This suggests that in small and medium-sized farms, competitiveness, and sustainability require entrepreneurs capable of achieving all commercial, environmental and social objectives with the help of a facilitator (Kim et al., 2019; Chi and Chien, 2022) who enables the transfer of innovations to as yet unexplored production systems, including Mediterranean tree crops (Mirčetić et al., 2022; Nsele et al., 2022).

Among the Mediterranean crops we are interested in, the most widespread tree crops such as olives, citrus fruits and vines still have a limited degree of innovation diffusion. Regarding crops such as olives and vines, these were considered in the study as irrigated crops, even though they are normally not. This scenario allows us to formulate the following research question:

"Farmers who grow Mediterranean tree crops, what level of propensity for innovation do they express?"

The aim of this question is to understand whether this innovation gap stems from a knowledge deficit, limited propensity, structural limitations or other reasons. It is therefore interesting to understand all the characteristics of entrepreneurs, farmers or professional managers (Hsieh and Kelley, 2016), who promote innovation, and why some organizations are able to generate innovation better than others (Unsworth et al., 2012; Mirzaei et al., 2016). Knowing the characteristics and determinants of the propensity to innovate in the primary sector becomes even more important because such information is fundamental to the design of public policies aimed at supporting and expanding demand (van Dijk et al., 2016; Small and Maseyk, 2022).

A company's decision to innovate is based on its ability to withstand the pressures of the process (Douthwaite and Hoffecker, 2017; Alam et al., 2021) and the degree of control it feels it has over the implementation of the innovation (Maizza et al., 2019; Harwiki and Malet, 2020). Since innovation requires a limited and sometimes complex decision-making process (Bechini et al., 2015), it is clear that those responsible for corporate innovation can be influenced by several objective and subjective variables (Brudermann et al., 2013; Montes de Oca Munguia et al., 2021). Determining the behavioral motivations and psychological factors of decision-makers in the agricultural industry is a rather complex task (Borges et al., 2014; Adnan et al., 2017; Mesa-Vázquez et al., 2021). The choice of a behavioral model is necessary (Berti and Mulligan, 2016) because the farm's intention to accept or not to accept an innovation inevitably clashes with human psychology, so we tried to analyze the factors and variables that influence this behavior (Judge et al., 2019; Hannus and Sauer, 2021).

To this end, a questionnaire was proposed to a sample of agricultural enterprises. This questionnaire aimed to detect the propensity to adopt an innovation that favors the sustainability of the production process, i.e., one that respects the environment, animals, health and workers' rights, as well as the resulting economic and environmental benefits. Several behavioral models have thus been identified to explain the decision-making process of entrepreneurs (Issa and Hamm, 2017; Lang and Rabotyagov, 2022), but among all the models proposed in the literature, we have chosen the Theory of Planned Behavior (TPB), which seems to be the most comprehensive tool for studying entrepreneurial behavior (Sok et al., 2021; Sarkar et al., 2022).

2. Materials and methods

2.1. The role of innovations in irrigation

Agricultural ecosystems play a key role in the conservation and availability of sufficient and quality water resources (Aznar-Sánchez et al., 2018), being the main providers of food but also the main consumers of water resources globally (Velasco-Muñoz et al., 2019; Shi et al., 2021). Irrigated agriculture is the primary user of intercepted water for human purposes, reaching a proportion exceeding 70–80% of the total in arid and semi-arid areas (Liu et al., 2017; López-Felices et al., 2020) food production that requires irrigation uses more than 40% of the total and uses only about 17% of the agricultural area (Saeed et al., 2021). The reduced availability of water resources for agri-food production systems increases the complexity of the social, economic and environmental implications in less developed regions (Gambelli et al., 2021). At present and even more so in the near future, irrigated crops can be grown under conditions of reduced water availability (Canaj et al., 2021; Pardo et al., 2022). Insufficient water resources will, therefore, be the norm rather than the exception and the emphasis of irrigation technology will shift from increasing productivity per unit area to maximizing water productivity (Ungureanu et al., 2020; Campana et al., 2022).

In this context, the solution to move toward is the development of knowledge and innovative solutions for the management and distribution of water resources to Mediterranean agro-productive systems, to make them more resilient to climate change, economically and technically efficient, sustainable, and able to contribute to the economic growth and development of the agricultural sector. The final recipient of such innovations is the agri-food chain, which, faced with climate change and water shortages, risks disrupting supplies of raw materials with quantity, but also quality and health standards (Pandya and Sharma, 2021; Dawit et al., 2022). But a second aspect to be emphasized is the benefit to the environment and water resources generated by innovations; indeed, every activity must be aimed at rationalizing the use of water in agriculture and containing the release of contaminants into the environment (Bowmer and Meyer, 2014). Since an increase in water endowments is not imaginable, the innovative solutions to be pursued must concern the integration of purified wastewater with traditional water endowments and, in particular, the improvement of water use efficiency. Improved irrigation efficiency can be achieved through innovation and technological adoption (Iocola et al., 2020; Tong et al., 2022). Water use efficiency depends on the technology and approach to irrigation (Velasco-Muñoz et al., 2019).

We therefore distinguish three main distribution methods in fruit tree plantations: surface (75% of agricultural land), sprinkler (20% of agricultural land) and micro-irrigation (5% of agricultural land) (Adeyemi et al., 2017; Rouzaneh et al., 2021). The application efficiencies of these general categories vary widely (Mateos et al., 2016; Al-Agele et al., 2021b). Micro-irrigation is generally the most efficient (80–90%) and surface irrigation is the least efficient (50–70%). The efficiency of sprinkler irrigation is 55–80% (Loures et al., 2020; Lopriore and Caliandro, 2022). In other words, the more efficient irrigation approach is used less and vice versa (Mateos et al., 2016). Emerging technologies, such as precision agriculture, agri-voltaic systems and technological innovation in irrigation (Loures et al., 2020), can further increase efficiency and productivity in the food-energy-water nexus (Assouline et al., 2015; Zhu et al., 2022). Precision agriculture in particular proves to be a potential technological ally for increasing water use efficiency (Turral et al., 2010; Pino et al., 2017). This type of agriculture includes decision support systems (DSS) (Bonfante et al., 2019; Souza and Rodrigues, 2022) to perform what-if analyses for managing small amounts of irrigation water, monitoring the water status of soil and/or vegetation (with remote sensing, proximal sensing and soil and vegetation sensors) and precision irrigation (Abioye et al., 2020, 2022).

Traditionally, irrigation was considered precise if the same amount of water could be distributed evenly over the entire surface area, without taking into account the spatial variability of the soil and vegetation (Cabarcas et al., 2019). In contrast, precision irrigation pursues the objective of adapting water supplies to actual crop needs on a small scale (Fernández et al., 2019; Jiménez et al., 2022). Precision irrigation is still underused (Al-Agele et al., 2021a; Beyá-Marshall et al., 2022), but farmer interest is high and would be rapidly implemented if supported by adequate technical dissemination entrusted to new professional figures (Bwambale et al., 2022; Silva et al., 2022).

2.2. The approach to innovations in Mediterranean tree crops

Mediterranean tree crops such as olives, citrus fruits and vines have deep roots in our country, which run deep into our history. They represent an important reality for Italy in the trade balance with foreign countries and for the economies of many parts of the country (Biasi et al., 2012; Sgroi et al., 2015). Although Italian fruit-growing cannot be defined as a homogeneous system, it often suffers from the same structural problems common to other agricultural systems (de Ollas et al., 2019), which are leading to a downsizing of cultivated areas and production, and faces similar challenges (Testa et al., 2015; Medda et al., 2022). In order to do this, awareness of the sector's critical issues must be raised: its future will depend on the strength of the ideas that entrepreneurs and technicians will translate into concrete actions. For the future, it will be essential to transfer useful innovation to farms, both process and product (Pereira et al., 2020), by introducing into common practice the results of the great advances made in the field of sensor technology, for precise and timely monitoring of orchard conditions (Campos et al., 2019; Yildirim et al., 2021).

It will be necessary to take greater advantage of advances in mechanization to simplify cultivation operations and lower production costs, both for canopy and soil management (Sarri et al., 2015; Campos et al., 2019; Kourgialas et al., 2019). Planting systems and forms of cultivation will have to be revisited in order to exploit their potential in passive defense against pathogens and pests and climatic adversities. The success of such agricultural enterprises will also increasingly depend on their ability to collect and exploit the large amount of data that will be generated, especially to control costs and increase the quality of production (Keswani et al., 2019). It is essential to invest in skills creation in a sector characterized by operational processes based more on generational skills and knowledge transfer than on innovation and process optimisation (Wolf et al., 2001). The most present and easy to take up innovation for these crops has always been genetics (de Ollas et al., 2019; Pinto et al., 2021). The varietal landscape of these species of 30 years ago has, in fact, been completely turned upside down and this type of varietal innovation is justified by the need to have "another" product to market (Parra-López et al., 2021). Technological innovation for these crops, on the other hand, has a much harder time penetrating (Kudryashova and Casetti, 2021; Dinelli et al., 2022), and hardly ever seems to do so through processes that guarantee impartiality on the part of those who issue technical advice that has a cost, and therefore must guarantee a return (Sarri et al., 2015; Montanaro et al., 2017). From various works in the literature, it appears to be that age is the factor that most counteracts the fruit grower's propensity to adopt innovation, while the first mitigating factor would appear to be the availability of a person to provide assistance in the event of difficulties (Chen and Liang, 2020).

This study will seek to understand which psychological constructs actually influence the innovation decision-making process of agricultural entrepreneurs growing Mediterranean tree crops, and to do so it will take into account the Theory of Planned Behavior (TPB) through an extended conceptual model where other factors come into play that influence the intention to implement sustainable irrigation innovations in agriculture and thus complement and extend the classical model.

2.3. Research questions

TPB provides a theoretical framework for the systematic study of factors influencing behavioral choices and has been widely used in other studies to analyze behaviors such as leisure choices, driving offenses, shoplifting and fraud (Zhang et al., 2015). The Theory of Planned Behavior (TPB) states that the decision to take a particular action is directly related to the individual's behavioral intentions (Hansson et al., 2012; Gao et al., 2017; Soorani and Ahmadvand, 2019). Intention (I) is, in turn, influenced by three factors (Figure 1):

1. Attitude (ATT), the individual's favorable or unfavorable assessment of performing a behavior.
2. Subjective norm (SN), the individual's perception of social pressure to perform or not perform a behavior.
3. Perceived behavioral control (PBC), the individual's perception of their ability to perform a behavior.

This study proposes an integration of the Theory of Planned Behavior (TPB) by including additional variables to increase its predictive accuracy (Joao et al., 2015; Rezaei et al., 2018; Tama et al., 2021; Sarkar et al., 2022). This conceptual model considers, in addition to the three classical TPB factors, namely attitude (A), subjective norms (SN) and perceived behavioral control (PBC), three other factors (Hou and Hou, 2019) such as perceived innovation characteristics (PIC), Benefits (B), and Transferability (T) and hypothesizes that all these six elements could directly or indirectly influence innovation intention (Wauters et al., 2010;

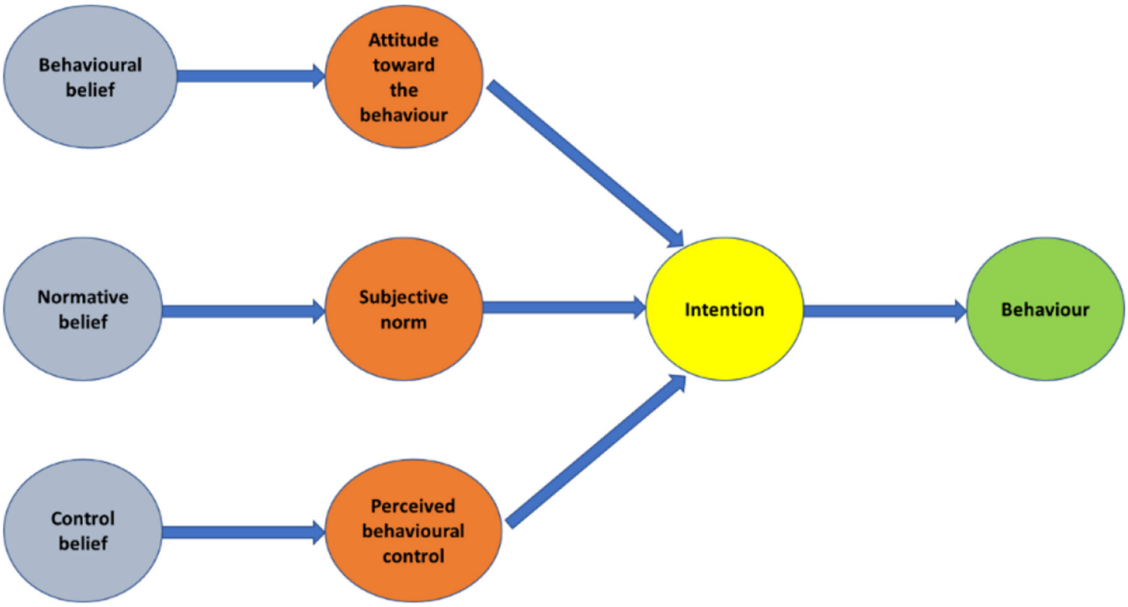


FIGURE 1
Theory of planned behavior*. *Our elaboration.

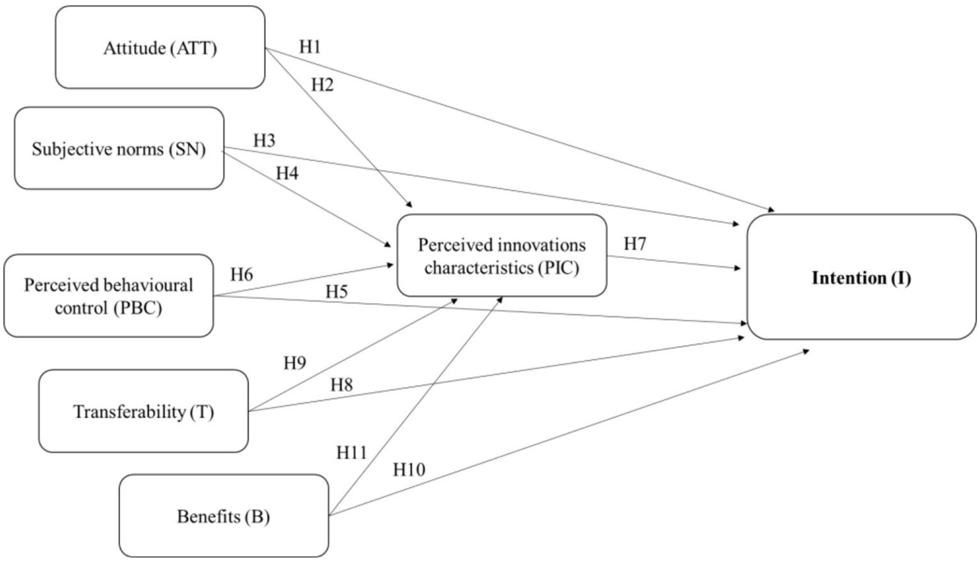


FIGURE 2
Extended theory of planned behavior model*. *Our elaboration.

Müller et al., 2021). In the indirect case, this would be due to the effect of perceived innovation characteristics (PIC), which act as a link between the other factors and intention (Figure 2).

Attitude toward the adoption of an innovation in agriculture refers to an individual's positive or negative evaluation of its implementation (Senger et al., 2017; Tóth et al., 2020). The second determinant of intention in TPB, is the subjective norm, which refers to the perceived social pressure on the person from the peer group, family, society or culture to perform the behavior under consideration (Tóth et al., 2020; Sarkar et al., 2022). The objective is therefore to detect whether the adoption of sustainable innovation in agriculture is conditioned by third parties. The third factor within the TPB model is perceived behavioral control (PBC) which refers to the sense of self-efficacy or ability with respect to a potential behavior (Tóth et al., 2020; Saeedi et al., 2022). The fourth element considered for the conceptual model is defined as characteristics of perceived innovations (PIC) and is taken from the theory of diffusion of innovations (Rogers, 1995). Rogers, in his theory, mentions five characteristics of an innovation that can affect the relative rate of adoption by different members of a social

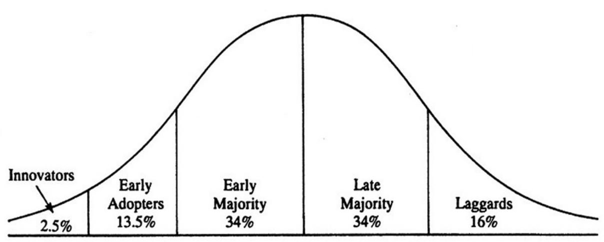


FIGURE 3
Diffusion of innovation theory. Source: Rogers (1995).

system: relative advantage, compatibility, complexity, observability and trialability. All these factors influence the decision to adopt or not to adopt technological innovation (Figure 3).

Among the additional variables considered, a further determinant of intention is transferability, which makes it possible to define whether the results of the experiment are transferable. Within the extended model, the final determinant of intention is the benefits, which allow the positive effects of innovation on the company to be measured.

Based on this knowledge, we formulated 11 hypotheses:

H1. Attitude toward the adoption of sustainable irrigation innovations in agriculture has a positive effect on behavioral intention.
H2. Attitude toward the adoption of sustainable irrigation innovations in agriculture has a positive effect on the characteristics of perceived innovations.
H3. Agricultural entrepreneurs, who perceived social pressure to adopt sustainable innovation, would be more likely to adopt it.
H4. Subjective norms have a positive effect on the characteristics of perceived sustainable irrigation innovations.
H5. Perceived behavioral control has a positive effect on the intention to innovate.
H6. Perceived behavioral control has a positive effect on perceived innovation characteristics.
H7. Perceived innovation characteristics have a positive effect on the intention toward the adoption of sustainable irrigation innovations in agriculture.
H8. The transferability of an innovation has a positive effect on the intention to innovate.
H9. The transferability of an innovation has a positive effect on the characteristics of perceived innovations.
H10. The benefits have a positive effect on the intention to innovate.
H11. Benefits have a positive effect on perceived innovation characteristics.

2.4. Data acquisition and processing

The survey to detect the propensity to adopt an innovation that favors the sustainability of the production process, i.e., respectful of the environment, animals, health and workers' rights, as well as the resulting economic and environmental benefits, was carried out through a specially designed questionnaire using the "Google Forms" tool and divided into 4 sections. It was disseminated online through the main social media channels between 6 June 2022 and 6 September 2022 with an active survey period of 90 days.

The first section deals with general information about the company, consisting of a series of questions about the company and the entrepreneur. The second section refers to the organizational choices of the surveyed farm manager, in terms of both needs and market. The third section concerns the analysis of the propensity to adopt an innovation. This section consists of a series of pre-defined questions designed to measure the behavior of the entrepreneur. The fourth section concerns the expected results following the adoption of an innovation. This section consists of a series of questions designed to capture key elements (such as perceived innovation characteristics, benefits and transferability of innovations) of the behavioral model. The latter two sections of the questionnaire are those concerning the TPB items in relation to the intention to adopt sustainable innovation and mostly use the 7-point Likert scale, where higher scores indicate greater compliance with the items, except for the benefits which were assessed on a multiple-choice format. Once the planning phase of the questionnaire had been completed and before starting data collection, we moved on to the control phase. At this stage, the necessary checks were carried out to ensure that there were no programming errors (bugs or malfunctions) and that the questionnaire was computerized appropriately to achieve the set research objectives. A total of 200 responses were collected from as many farms, of which 125 were selected as suitable for data analysis.

Previous studies have largely focused on socio-economic characteristics and ignored psychological factors influencing adoption intention (Borges et al., 2019). Instead, in this study, we sought to examine psychological factors by hypothesizing that these could explain greater variation in the dependent variable (the intention to implement innovation) than the socio-economic characteristics of farmers. The study aims to verify whether the TPB variables, together with transferability and benefits, predict the intention in relation to the adoption of sustainable innovation in agriculture. The data were analyzed using the Statistical Package for the Social Sciences (SPSS) version 27. First, we cleaned and checked the data to identify any missing values or irregularities. Secondly, we calculated descriptive statistics (e.g., averages and standard deviations). We checked the quality and adequacy of the measurement model and, through exploratory factor analysis (EFA), attempted to associate the variables with the various latent factors. Next, Pearson correlation coefficients were calculated to assess the correlation between the factors (Adnan et al., 2018). Therefore, we tested the causal relationships between the different factors of the TPB model with integrations by means of a hierarchical regression analysis, where we entered intention as the dependent variable and the TPB constructs as independent variables in the first stage, and then in the second stage we entered PIC as the dependent variable and the remaining constructs as independent variables (Saeedi et al., 2022).

TABLE 1 Socio-economic characteristics*.

Variables	Description	Frequency	Percentage (%)
Gender	Male	118	94.4
	Female	7	5.6
Age	<30	18	14.4
	31–50	71	56.8
	>51	36	28.8
Farm management title	Direct farmer	6	4.8
	Professional farmer	106	84.8
	Other	13	10.4
Legal form	Individual company	14	11.2
	Simple company	105	84
	Capital companies (Srl, Spa, ecc)	6	4.8
Size of farm (in hectares)	Small (<5 hectares)	52	41.6
	Medium (5–20 hectares)	61	48.8
	Large (> 20 hectares)	12	9.6
Main production address	Citrus	24	19.2
	Other Fruits	24	19.2
	Olive	22	17.6
	Horticulture/ Citrus	14	11.2
	Viticulture	14	11.2
	Cereals/Citrus	14	11.2
	Forager/ Zootechnical/ Other Fruits	1	0.8
	Other	12	9.6
Educational level	Primary school license	21	16.8
	Secondary school certificate	22	17.6
	High school diploma	40	32
	Degree	42	33.6
Is the business run only by family labor?	Yes	65	52
	No	60	48

*Our elaboration.

3. Results

3.1. Socio-economic profile of participants

The results described in Table 1, show that the majority of respondents (94.4%) were male, confirming that the role of women is still marginal. Most of the respondents were between 31 and 50 years old (56.8%), while only 14.4% of the respondents were young people under 30. With regard to the legal form of the companies surveyed, it emerges that 84.8% of them are run by professional agricultural entrepreneurs and the form that prevails is that of the "Simple Company", which accounts for 84% of the companies surveyed. With regard to farm size, we note that 48.80% of the farms cover an area of between 5 and 20 hectares, 41.60% have an area of less than 5 hectares and only 9.60% are identified as large farms with an area of more than 50 hectares. Looking at the production addresses, however, a homogeneous distribution appears, with citrus (19.2%), fruit (19.2%), and olive (17.6%) being most present, and only the mixed fodder/fruit address showing a very low percentage (0.8%) with only one answer. Most of the respondents (33.6%) completed their education, while 16.8% completed only primary education and 17.6% completed secondary education. Finally, with regard to the labor used in the company, 52% of the companies surveyed use family labor, the remainder (48%) use external labor.

The analysis of the questionnaires made it possible to construct Figure 4, which well expresses with a visual element the frequency with which a 'word or phrase' connected with a sustainable irrigation innovation is used by entrepreneurs in relation to other words in an irrigation dataset. In our case, the evaluations proposed in the optimization of water use were related to a number of parameters among the many possible ones and, among them, were considered:

- the quality of irrigation water;
- the cultivation method adopted (agronomic practices);
- the irrigation method used;
- the management of irrigation;
- the choice of when to irrigate (i.e., knowledge of the crop's evapotranspiration).

Minimization of water losses can be ensured through different agronomic practices such as (i) mulching, use of (ii) grafted plants and (iii) biostimulants. Mulching, in addition to preventing weed growth, reduces evapotranspiration, improves root growth and the uptake of water and nutrients, and increases water use efficiency. Similarly, the use of grafted plants, due to the better net CO_2 assimilation and transpiration efficiency and the greater development of the root system, is another valid strategy to help reduce irrigation volumes. Not least, the use of microbial and non-microbial bio-stimulants can improve the morphological and physiological characteristics of crops, enhancing their productive performance and contributing to a more virtuous use of water resources.

The arboreal and mixed (arboricultural and other) farms that participated in the survey stated that they adopt an irrigation sustainability strategy partly for ethical reasons and

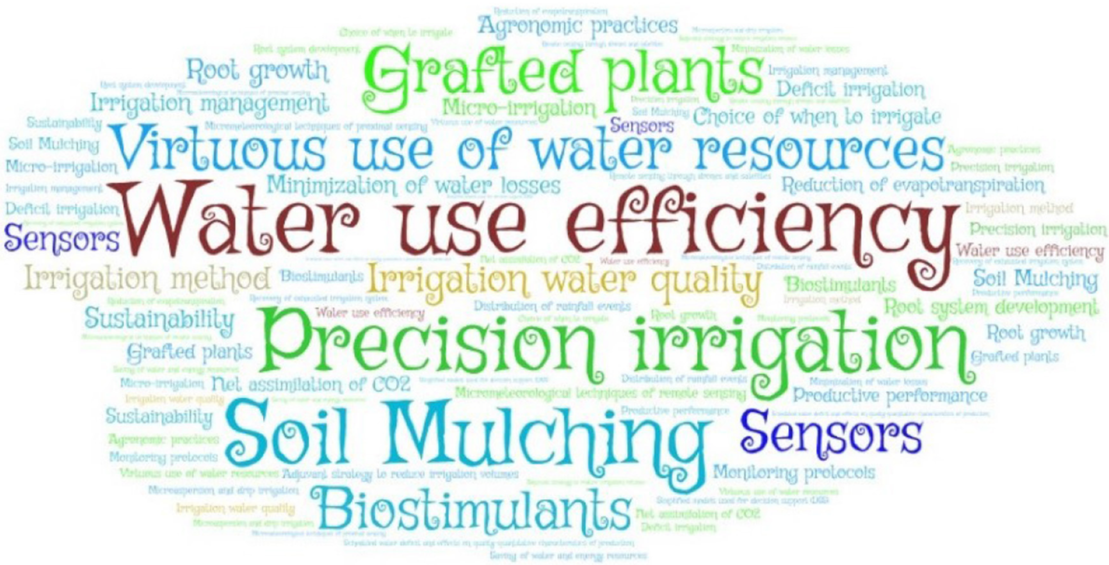


FIGURE 4
Frequency of relationships between words or phrases relevant to sustainable irrigation innovations*. *Our elaboration.

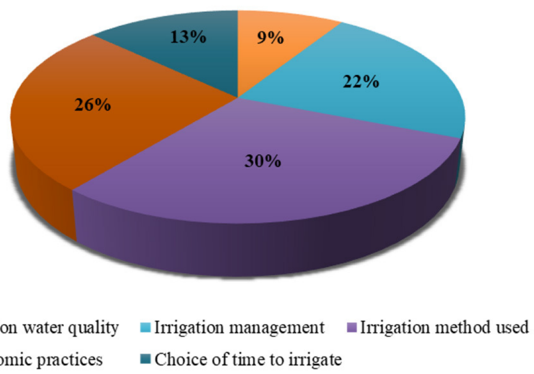


FIGURE 5
Sustainable irrigation innovations adopted by the sample of farms surveyed*. *Our elaboration.

partly to optimize water and energy consumption and achieve adequate levels of economic-productive performance (Figure 5). On the initiatives undertaken, in some cases there has been a prior study of the terrain, the type of planting and the characteristics of the irrigation service (with substantial differences between those who own irrigation investments such as wells, storage tanks, etc.) and those who acquire water from a public body in charge of the purpose (irrigation consortium mainly, which entails irrigation shifts, operating pressure, watering volumes, etc. that are not always dependent on their own will). Innovations in irrigation techniques include sprinkler and micro-irrigation systems. Drip lines are also widely used with micro-sprinklers to combine the positive effects of a drip system with overhead sprinklers. Finally, innovations in irrigation strategies were limited, such as the use of deficit irrigation combined with micro meteorological remote sensing and proximal sensing technologies, probably also due to the lack of adequate expertise.

3.2. Latent variables and extended model measurements

In order to extract latent variables from the questionnaire items, exploratory factor analysis (EFA) was used. Through the KMO and Bartlett's verification tests, it was possible to confirm the validity of the extended TPB model comprising seven latent factors indicating intention, attitude, subjective norm, PBC, PIC, benefit and transferability. The results show an adequate fit of the model (Kaiser-Meyer-Olkin measure of sampling adequacy = 0.66, Bartlett's test of sphericity with Sign < 0.001). Table 2 shows the number of items considered for the extraction of each latent factor and their standardized factor loadings. Each item corresponds to a question on the questionnaire that was measured by entering a single scale from 1 to 7 differentiated by individual question, where value 1 means Not at all agree/Absolutely unlikely and value 7 means Completely agree/Absolutely likely. Item factor loadings below 0.50 were discarded from the analysis. In order to assess the internal consistency and reliability of the scale, the study estimated Cronbach's alpha coefficients for each factor. Cronbach's alpha to assess internal consistency can be classified as: excellent ($\alpha \geq 0.9$), good ($0.7 \leq \alpha < 0.9$), acceptable ($0.6 \leq \alpha < 0.7$), poor ($0.5 \leq \alpha < 0.6$), and unacceptable ($\alpha < 0.5$). The results show adequate internal consistency of the scale items, as Cronbach's alpha coefficients range from 0.70 to 0.96. In addition, descriptive analyses of the items were conducted and the table shows the mean and standard deviation, with the highest mean value for attitude and the lowest for benefits.

TABLE 2 Reliability, factor loading, mean and SD*.

Variables	Observed items	α	Factor loading	Mean	Standard deviation
Intention	3	0.963	0.940	4.70	1.116
			0.985	4.80	1.075
			0.920	4.79	1.070
Attitude	3	0.707	0.913	4.97	0.965
			0.930	5.06	0.940
			0.738	4.89	1.073
Subjective norm	6	0.925	0.636	3.12	0.945
			0.944	3.85	1.229
			0.860	3.87	1.200
			0.890	3.90	1.215
			0.816	3.77	1.180
			0.838	3.59	1.138
Perceived behavior control	7	0.865	0.856	3.90	1.202
			0.830	3.65	1.067
			0.843	3.80	1.133
			0.535	3.77	1.109
			0.786	2.96	1.363
			0.767	3.52	1.199
			0.976	3.27	1.352
Perceived innovation characteristics	10	0.951	0.800	4.44	1.068
			0.800	4.46	1.065
			0.799	4.36	1.091
			0.772	4.40	1.053
			0.794	4.32	1.089
			0.805	4.29	1.080
			0.861	4.55	1.133
			0.829	4.59	1.240
			0.845	4.52	1.045
			0.786	4.47	1.122
Benefits	4	0.721	0.707	2.84	0.520
			0.538	2.32	0.591
			0.693	2.52	0.608
			0.652	2.80	0.603
Transferability	7	0.802	0.787	4.61	1.050
			0.574	3.95	0.917
			0.723	4.09	0.900
			0.778	4.04	0.849
			0.660	4.08	0.834
			0.607	4.15	0.794
			0.641	4.01	0.852

*Our elaboration.

TABLE 3 Correlation matrix*.

	INT	ATT	SN	PBC	PIC	B	T
INT	–						
ATT	0.626♦♦	–					
SN	0.640♦♦	0.421♦♦	–				
PBC	0.242♦♦	0.077	0.284♦♦	–			
PIC	0.430♦♦	0.319♦♦	0.537♦♦	0.212♦	–		
B	0.618♦♦	0.492♦♦	0.420♦♦	0.247♦♦	0.529♦♦	–	
T	0.158	−0.104	0.238♦	−0.036	0.498♦♦	0.212♦	–

*Our elaboration. ♦♦Correlation is significant at the 0.01 level (two-tailed). ♦Correlation is significant at the 0.05 level (two-tailed). Int, Intention; Att., Attitude; SN, Subjective norm; PBC, Perceived behavior control; PIC, Perceived innovation characteristics; B, Benefits; T, Transferability.

3.3. Correlations between variables

The results of Pearson's correlation coefficient test between the variables are shown in Table 3, which reveals significantly positive correlations between intention and all other variables in the model with the exception of transferability. There is also a good correlation between the variables, with a few exceptions, e.g., aptitude appears to be uncorrelated with PBC and transferability, just as there is no correlation between PBC and transferability itself, which appears to be the most problematic variable in this respect.

3.4. Behavior of the entrepreneur

In order to test the general relationships between the variables and thus answer the assumptions made, two different linear regressions were conducted. The first was performed in order to understand which variables influence the intention to adopt the innovation and therefore intention was set as the dependent variable and TPB constructs as independent variables. The second regression was aimed at understanding the mediating effect exerted by the characteristics of perceived innovations (PIC) against intention for the other variables, thus setting PIC as the dependent variable. With regard to the first regression, the ANOVA table shows an *F*-value of 11.43 and a significance level p of <0.001, the regression model therefore fitted well. The summary table of the model shows that R2 has a value of 0.52, which indicates that 52% of the variance of intention can be explained by attitude (ATT), subjective norm (SN), perceived behavioral control (PBC), perceived innovation characteristics (PIC), benefits (B) and transferability. The results in Table 4 show that intention is strongly determined by attitude (ATT) as the most important variable influencing behavior (B: 0.337, significance level $p < 0.001$). Subjective Norms (SN) (B: 0.377, significance level $p = 0.001$) and Perceived Innovations Characteristics (PIC) (B: 0.263, significance level = 0.008) also show a good level of influence toward intention. The remaining factors such as perceived behavioral control (PBC) (B: 0.042, significance level $p = 0.647$), benefits (B) (B: −0.044, significance level $p = 0.651$) and transferability (T) (B: −0.077, significance level $p = 0.449$), as we expected, do not directly influence intention.

The second regression shows an ANOVA table with F equal to 17.84 and a significance level p equal to <0.001, the regression model therefore fitted well. The summary table of the model shows that the R2 has a value of 0.58, which indicates that 58% of the variance in the characteristics of perceived innovations can be explained by attitude (ATT), subjective norm (SN), perceived behavioral control (PBC), benefits (B), and transferability. The results in Table 5 show that perceived behavioral control (PBC) is directly related to PIC (B: 0.222, significance level $p = 0.007$), the same applies to benefits (B) (B: 0.211, significance level $p = 0.010$) and transferability (T) (B: 0.354, significance level $p < 0.001$).

The results show, therefore, that only attitude (ATT) subjective norms (SN) directly influence the intention to adopt sustainable irrigation innovations in agriculture (I). Other factors such as perceived behavioral control (PBC), benefits (B), and transferability (T), indirectly influence intention, due to the effect of perceived innovation characteristics (PIC), which influences intention (I) by acting as a mediator between PBC, T, B with I, and thus acting on the psychology of the individual.

4. Discussion

Innovation in agriculture is an increasingly relevant topic. It is seen as a broad concept that includes the creation and/or adoption of innovations that may be new to the enterprise, new to the market or new to the world (Kalaitzandonakes et al., 2018; Despotović et al., 2019). It is absolutely necessary to enable Italian farmers to benefit from technological innovation because growth and sustainable development inevitably also come from knowledge transfer. We must innovate for a sustainable future. The role of agriculture is increasingly strategic in responding to major global challenges such as growing food demand, climate change, the energy crisis, and natural resource scarcity. But in order to produce more and better, polluting less, the primary sector must be able to count on large investments in research and innovation: only from here can the answers come to combine increased farm income and food resources, without altering the already too fragile environmental balance. The management of water resources, in relation to current climate changes, will lead to a rational use together with the analysis of specific crop needs in order to avoid any form of waste. In this scenario, the choice in farm cropping will increasingly shift toward crops with lower water requirements and water-saving distribution

TABLE 4 Regression coefficients*.

Model	Unstandardized coefficients		Standardized coefficients	t	Sign.
	B	Standard error	Beta		
(Costant)	−0.006	0.071		−0.083	0.934
ATT	0.314	0.087	0.337	3.627	<0.001
SN	0.360	0.107	0.377	3.361	0.001
PBC	0.031	0.067	0.042	0.460	0.647
PIC	0.369	0.183	0.263	2.013	0.008
B	−0.042	0.092	−0.044	−0.454	0.651
T	−0.070	0.092	−0.077	−0.761	0.449

*Our elaboration.

TABLE 5 Regression coefficients*.

Model	Unstandardized coefficients		Standardized coefficients	t	Sign.
	B	Standard error	Beta		
(Costant)	0.138	0.044		3.145	0.002
ATT	0.065	0.057	0.097	1.137	0.260
SN	0.082	0.059	0.102	1.274	0.179
PBC	0.116	0.042	0.222	2.766	0.007
B	0.142	0.058	0.211	2.433	0.010
T	0.229	0.054	0.354	4.217	<0.001

*Our elaboration.

methods. Regarding the first point, relating to reductions in water requirements, these may result from the application of agronomic techniques, the choice of rootstock-graft combination as well as mass selections in the field. With regard to the second point, the current trend is toward micro-aspersion methods (Kourgialas et al., 2022) together with the application of water deficit techniques, which in some cases save water and improve crop quality. The trend is to develop true precision irrigation, which will allow the plant to always be guaranteed the amount of water it needs (Adeyemi et al., 2017; Velasco-Muñoz et al., 2019; Caruso et al., 2021) based on a system of information that will come to us from farm big data, collected by a network of sensors and weather sheds capable of managing irrigation through practices that connect to artificial intelligence as the new challenge of agriculture 4.0.

The Mediterranean tree crop production sector is experiencing difficult years that have led in some cases to a sharp downsizing of cultivated areas. Phytosanitary and climatic emergencies, product remunerations that are often lower than production costs, structural and bureaucratic problems have put many fruit farms to the test (Sgroi et al., 2015; Kourgialas et al., 2022). The challenge for the future is certainly to maintain high yields and fruit quality while using fewer resources. It will not be enough to produce new knowledge; much will depend on the ability of production systems to quickly introduce the right innovations in the fields (Caruso et al., 2021). There will be an increasing need for up-to-date and high-profile technical-scientific dissemination. Taking the adoption of innovation as a point of view, the contribution of this research is useful to explore the behavioral intentions of farmers cultivating Mediterranean tree crops toward the intention to adopt innovations.

The study aims to test the predictive validity of an extended TPB model, which considers not only the classical three variables, but also the characteristics of perceived innovations, transferability and benefits in relation to the adoption of innovations in agriculture. The results confirmed that the extended TPB is a useful model to clarify which psychological factors drive citrus, grapevine and olive entrepreneurs in adopting innovations. The results suggest that attitude, subjective norms and PIC significantly influence intention, thus supporting Hypotheses 1, 3, and 7, respectively. Whereas, PBC, transferability and benefits are significantly influential in explaining PIC but do not directly influence intention to innovate. Thus, Hypotheses 5, 9, and 11 hold, but Hypotheses 6, 8, and 10 are not significant and are therefore rejected. Hypotheses 2 and 4 are rejected, as the values are found to be non-significant and prove that PIC is not influenced by attitude and subjective norms. The results showed that entrepreneurs' intentions to adopt an innovation are explained by attitudes toward innovation adoption and subjective norms. Indeed, of all the variables, they are the most influential in predicting the adoption of sustainable innovation in agriculture. The greater impact of attitude and subjective norms on intentions in relation to the other constructs reveals that the people with whom we relate have such a significant influence that they have power over choice behavior. Perceived innovation characteristics are also significant predictors of entrepreneurs' intention to innovate. The impact of PIC on intentions suggests that less uncertainty and concern for companies, which often face a number of unfavorable factors (low financial resources, high costs, lack of knowledge about innovations), could be helpful in increasing intentions. Perceived behavioral control, transferability and benefits do not appear to have a direct impact on intention, but indirectly through the mediating effect of PIC, with positive values.

Current efforts to improve quality, company design and technological conditions are very low, confirming our study, as 53.2% of the companies stated that they had not made any innovations in the 5 years prior to the interview. Our analysis confirmed that entrepreneurs' positive attitude toward innovation directly increases their intention to implement more innovation. In summary, this study confirmed the predictive validity of TPB, with the integration of PIC, transferability and benefits, to explain the entrepreneur's intention to adopt sustainable innovations in agriculture.

5. Conclusion

The value of innovation as a fundamental strategy for growth policies and the development of competitiveness in the primary sector has strengthened over the years, acquiring ever greater dimensions. Indeed, it is regarded as an important and necessary component for the development of agricultural activities (Bowman and Zilberman, 2013; Spendrup and Fernqvist, 2019). In order to effectively motivate landowners' behavior toward innovation, policy-makers need to understand the characteristics of the decision-makers that influence their intentions to adopt various innovations, highlighting the importance of both observable and unobservable factors underlying farmers' decisions. Our study sought to address this need by identifying which unobservable socio-psychological factors influence farmers' intentions. Indeed, this study adds a contribution to the existing scientific literature by analyzing the psychological factors influencing the intentions of farmers producing Mediterranean tree crops toward the application of sustainable irrigation innovations based on an extended TPB model, especially in the context of a developing agro-economy.

The results indicate that, TPB factors can explain farmers' behavioral intentions to apply on-farm innovations, but also that the addition of three other constructs (PIC, benefits, and transferability) in the TPB framework can increase the predictive power and accuracy of the theory. Based on our results, it can be seen that the direct effect on the intention to innovate is negative, although the direct influence on innovation is positive. This means that the companies studied would like to innovate, but feel that their innovation capabilities are not sufficient to implement adequate innovation projects. Our analysis confirmed that entrepreneurs' positive attitude toward innovation directly increases the intention to implement more innovation, as it is a significant predictor of intention. Furthermore, based on the greater impact of subjective norms on intention, it appears that the combination of extension services to improve the level of knowledge on the importance of innovations could significantly influence farmers' attitudes on the intention to apply them.

In particular, given the direct effect of PIC on intention, communication policies aimed at promoting the adoption of sustainable innovations by farmers should mainly emphasize their characteristics and the benefits they can bring to businesses. These policies could be coordinated by public authorities (in Italy, mainly the Ministry of the Environment and Agricultural Policies) and environmental associations (e.g., Legambiente, WWF, etc.). These organizations could devise and disseminate messages that attract farmers with an innovative vision and try to stimulate the modernization of the agri-food system, e.g., through workshops, meetings on this topic or even *ad hoc* training programmes and/or projects with developers of agricultural innovations.

We recognize the limitations of this study, pointing out that other factors not considered may also influence actual behavior between the time the intention is formed and its translation into practice. The model proposed in this study did not consider farmers' emotions, e.g., fear/threat, positive or negative feelings. The literature has, in fact, shown that this is an inherent weakness of TPB, as no human behavior is independent of emotions (Zhang, 2018). Moreover, farmers are more likely to adopt less risky agricultural practices and technologies when the existing production risk is high (Beyene and Kassie, 2015). Therefore, in order to identify farmers' intentions toward the implementation of on-farm innovations, we suggest adding other psychological constructs, e.g., risks, subsidies or government incentives to future studies. Despite the limitations, however, it is believed that the study contributes to the growth of a line of research based on the intention to innovate in agriculture, because it succeeds in highlighting the benefits of combining economic and psychological perspectives through the study of the entrepreneur's intentions.

The future of the implementation of innovations in agriculture will be facilitated by the upcoming availability of PNRR funds. Following the enactment of the EU's Next Generation Plan, the Italian agricultural system, through the National Recovery and Resilience Plan (PNRR), will have the opportunity to utilize special measures dedicated to the country's green and digital development. From a total of EUR 750 billion, Italy has been allocated EUR 191.5 billion (70 in grants and 121 in loans) of which a large part is earmarked for production systems. In this context, it will be crucial to define management models and innovation packages that favor innovation in productive agricultural systems, including irrigation, so that the implementation of innovations does not present barriers to entry and allows for a rapid and profitable nationwide diffusion in all production systems, based on the assumption that without innovation there is no future. The recent enactment of the Ministry of Agriculture and Food Sovereignty also focuses on the role of agricultural production from an economic, social and environmental perspective, objectives that can be achieved today thanks to the process and product innovations available as a result of the Digital Transformation taking place with artificial intelligence in the forefront.

In conclusion, this study may help to formulate future research that can combine psychological and socio-economic factors to understand the dynamics of innovation adoption and we are confident that this would help to understand whether future findings from other countries will follow the patterns highlighted in this study and/or how the difficulties encountered in innovation have been addressed.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Funding

Miglioramento delle produzioni agroalimentari mediterranee in condizioni di carenza di risorse idriche -WATER4AGRIFOOD- cod. CUP: B64I20000160005, PON RICERCA E INNOVAZIONE 2014-2020, Azione II-Obiettivo Specifico 1b, and "Sostenibilità ed innovazioni della ricerca in agricoltura, alimentazione ed ambiente", Scientific Responsible Prof. Mario D'amico, UPB: 5A722192180.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abioye, E. A., Abidin, M. S. Z., Mahmud, M. S. A., Buyamin, S., Ishak, M. H. I., Rahman, M. K. I. A., et al. (2020). A review on monitoring and advanced control strategies for precision irrigation. *Comput. Electron. Agric.* 173, 105441. doi: 10.1016/j.compag.2020.105441

Abioye, E. A., Hensel, O., Esau, T. J., Elijah, O., Abidin, M. S. Z., Ayobami, A. S., et al. (2022). Precision irrigation management using machine learning and digital farming solutions. *AgriEng.* 4, 70–103. doi: 10.3390/agriengineering4010006

Adeyemi, O., Grove, I., Peets, S., and Norton, T. (2017). Advanced monitoring and management systems for improving sustainability in precision irrigation. *Sustainability* 9, 353. doi: 10.3390/su9030353

Adnan, N., Nordin, S. M., and Ali, M. (2018). A solution for the sunset industry: Adoption of Green Fertiliser Technology amongst Malaysian paddy farmers. *Land Use Policy* 79, 575–584. doi: 10.1016/j.landusepol.2018.08.033

Adnan, N., Nordin, S. M., and bin Abu Bakar, Z. (2017). Understanding and facilitating sustainable agricultural practice: A comprehensive analysis of adoption behaviour among Malaysian paddy farmers. *Land Use Policy* 68, 372–382. doi: 10.1016/j.landusepol.2017.07.046

Aksoy, H. (2017). How do innovation culture, marketing innovation and product innovation affect the market performance of small and medium-sized enterprises (SMEs)? *Technol. Soc.* 51, 133–141. doi: 10.1016/j.techsoc.2017.08.005

Al-Agele, H. A., Nackley, L., and Higgins, C. (2021a). Testing novel new drip emitter with variable diameters for a variable rate drip irrigation. *Agriculture* 11, 1–8. doi: 10.3390/agriculture11020087

Al-Agele, H. A., Nackley, L., and Higgins, C. W. (2021b). A pathway for sustainable agriculture. *Sustainability* 13, 4328. doi: 10.3390/su13084328

Alam, S. S., Ahmad, M., Othman, A. S., Shaari, Z. B. H., and Masukujjaman, M. (2021). Factors affecting photovoltaic solar technology usage intention among households in Malaysia: Model integration and empirical validation. *Sustainability* 13, 1–20. doi: 10.3390/su13041773

Asadi, E., Isazadeh, M., Samadianfard, S., Ramli, M. F., Mosavi, A., Nabipour, N., et al. (2020). Groundwater quality assessment for sustainable drinking and irrigation. *Sustainability* 12, 177. doi: 10.3390/su12010177

Assouline, S., Russo, D., Silber, A., and Or, D. (2015). Balancing water scarcity and quality for sustainable irrigated agriculture. *Water Resour. Res.* 51, 3419–3436. doi: 10.1002/2015WR017071

Aznar-Sánchez, J. A., Belmonte-Ureña, L. J., Velasco-Muñoz, J. F., and Manzano-Agugliaro, F. (2018). Economic analysis of sustainable water use: A review of worldwide research. *J. Cleaner Prod.* 198, 1120–1132. doi: 10.1016/j.jclepro.2018.07.066

Bafdal, N., Dwiratna, S., Suryadi, E., and Kendarto, D. R. (2018). Water harvesting as a technological innovation and greater solving of climatic change impact to supply fertigation. *Int. J. Adv. Sci. Eng. Inf. Technol.* 8, 2380–2385. doi: 10.18517/ijaseit.8.6.7697

Barth, H., Ulvenblad, P. O., and Ulvenblad, P. (2017). Towards a conceptual framework of sustainable business model innovation in the agri-food sector: A systematic literature review. *Sustainability* 9, 1620. doi: 10.3390/su9091620

Bechini, L., Costamagna, C., Zavattaro, L., Grignani, C., Bijttebier, J., and Ruysschaert, G. (2015). Barriers and drivers towards the incorporation of crop residue in the soil. Analysis of Italian farmers' opinion with the theory of planned behaviour. *Italian J. Agron.* 10, 178–184. doi: 10.4081/ija.2015.663

Berti, G., and Mulligan, C. (2016). Competitiveness of small farms and innovative food supply chains: The role of food hubs in creating sustainable regional and local food systems. *Sustainability* 8, 616. doi: 10.3390/su8070616

Beyá-Marshall, V., Arcos, E., Seguel, Ó., Galleguillos, M., and Kremer, C. (2022). Optimal irrigation management for avocado (cv.'Hass') trees by monitoring soil water content and plant water status. *Agric. Water Manage.* 271, 107794. doi: 10.1016/j.agwat.2022.107794

Beyene, A. D., and Kassie, M. (2015). Speed of adoption of improved maize varieties in Tanzania: An application of duration analysis. *Technol. Forec. Soc. Change* 96, 298–307. doi: 10.1016/j.techfore.2015.04.007

Biasi, R., Botti, F., Barbera, G., and Cullotta, S. (2012). The role of Mediterranean fruit tree orchards and vineyards in maintaining the traditional agricultural landscape. *Acta Horticulturae* 940, 79–88. doi: 10.17660/ActaHortic.2012.940.9

Bigliardi, B., and Filippelli, S. (2022). Sustainability and open innovation: main themes and research trajectories. *Sustainability* 14, 6763. doi: 10.3390/su14116763

Bonfante, A., Monaco, E., Manna, P., de Mascellis, R., Basile, A., Buonanno, M., et al. (2019). LCIS DSS—An irrigation supporting system for water use efficiency improvement in precision agriculture: A maize case study. *Agric. Syst.* 176, 102646. doi: 10.1016/j.agsy.2019.102646

Borges, J. A. R., Oude Lansink, A. G. J. M., and Emvalomatis, G. (2019). Adoption of innovation in agriculture: A critical review of economic and psychological models. *Int. J. Innov. Sustain. Develop.* 13, 36–56. doi: 10.1504/IJISD.2019.096705

Borges, J. A. R., Oude Lansink, A. G. J. M., Marques Ribeiro, C., and Lutke, V. (2014). Understanding farmers' intention to adopt improved natural grassland using the theory of planned behavior. *Livestock Sci.* 169, 163–174. doi: 10.1016/j.livsci.2014.09.014

Bowman, M. S., and Zilberman, D. (2013). Economic factors affecting diversified farming systems. *Ecol. Soc.* 18, 14. doi: 10.5751/ES-05574-180133

Bowmer, K. H., and Meyer, W. S. (2014). "Irrigation agriculture: Sustainability through holistic approaches to water use and innovation," in *Drinking Water and Water Management: New Research* 181–224.

Brudermann, T., Reinsberger, K., Orthofer, A., Kislinger, M., and Posch, A. (2013). Photovoltaics in agriculture: A case study on decision making of farmers. *Energy Policy* 61, 96–103. doi: 10.1016/j.enpol.2013.06.081

Bwambale, E., Abagale, F. K., and Anornu, G. K. (2022). Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. *Agric. Water Manage.* 260, 107324. doi: 10.1016/j.agwat.2021.107324

Cabarcas, A., Arrieta, C., Cermeno, D., Leal, H., Mendoza, R., and Rosales, C. (2019). "Irrigation system for precision agriculture supported in the measurement of environmental variables," in *Proceedings - 2019 7th International Engineering, Sciences and Technology Conference, IESTEC* 2019, 671–676. doi: 10.1109/IESTEC46403.2019.00125

Campana, P. E., Lastanao, P., Zainali, S., Zhang, J., Landelius, T., and Melton, F. (2022). Towards an operational irrigation management system for Sweden with a water–food–energy nexus perspective. *Agric. Water Manage.* 271, 107734. doi: 10.1016/j.agwat.2022.107734

Campos, J., Llop, J., Gallart, M., García-Ruiz, F., Gras, A., Salcedo, R., et al. (2019). Development of canopy vigour maps using UAV for site-specific management during vineyard spraying process. *Prec. Agric.* 20, 1136–1156. doi: 10.1007/s11119-019-09 643-z

Canaj, K., Morrone, D., Roma, R., Boari, F., Cantore, V., and Todorovic, M. (2021). Reclaimedwater for vineyard irrigation in a mediterranean context: Life cycle environmental impacts, life cycle costs, and eco-efficiency. *Water* 13, 2242. doi: 10.3390/w13162242

Capitanio, F., Coppola, A., and Pascucci, S. (2010). Product and process innovation in the Italian food industry. *Agribusiness* 26, 503–518. doi: 10.1002/agr.20239

Caruso, G., Palai, G., Caruso, M., Roccuzzo, G., Stagno, F., Zarco-Tejada, P. J., et al. (2021). Using an unmanned platform and VIS-NIR cameras to determine biophysical and geometrical parameters of olive, grapevine and citrus canopies. *Acta Horticulturae* 1314, 345–352. doi: 10.17660/ActaHortic.2021.1314.43

Chen, C. C., and Liang, C. (2020). Evoking agriculture entrepreneurship: How younger and older farmers differ. *Sustainability* 12, 7005. doi: 10.3390/su12177005

Chi, S. Y., and Chien, L. H. (2022). Influence of ecological and quality concerns on the adoption intention of environment-smart agricultural systems. *Appl. Ecol. Environ. Res.* 20, 363–381. doi: 10.15666/aeer/2001_363381

Coghlan, C., Labrecque, J. A., Ma, Y., and Dub,é, L. (2020). A biological adaptability approach to innovation for small and medium enterprises (SMEs): Strategic insights from and for health-promoting agri-food innovation. *Sustainability* 12, 4227. doi: 10.3390/su12104227

Curry, G. N., Nake, S., Koczberski, G., Oswald, M., Rafflegeau, S., Lummani, J., et al. (2021). Disruptive innovation in agriculture: Socio-cultural factors in technology adoption in the developing world. *J. Rural Stud.* 88, 422–431. doi: 10.1016/j.jrurstud.2021.07.022

Dawit, M., Dinka, M. O., and Halefom, A. (2022). Farmers' perception of climate change and gender sensitive perspective for optimised irrigation in a compound surface-ground water system. *J. Water Land Develop.* 52, 265–271.

de Oliveira Padilha, L. G., Malek, L., and Umberger, W. J. (2022). Consumers' attitudes towards lab-grown meat, conventionally raised meat and plant-based protein alternatives. *Food Quality and Preference* 99. doi: 10.1016/j.foodqual.2022.104573

de Ollas, C., Morillón, R., Fotopoulos, V., Puértolas, J., Ollitrault, P., Gómez-Cadenas, A., et al. (2019). Facing climate change: Biotechnology of iconic mediterranean woody crops. *Front. Plant Sci.* 10, 427. doi: 10.3389/fpls.2019.00427

Despotović, J., Rodić, V., and Caracciolo, F. (2019). Factors affecting farmers' adoption of integrated pest management in Serbia: An application of the theory of planned behavior. *J. Cleaner Prod.* 228, 1196–1205. doi: 10.1016/j.jclepro.2019.04.149

Dinelli, G., Chen, Q., Scuderi, A., Via, G., la, Timpanaro, G., and Sturiale, L. (2022). The digital applications of "Agriculture 4.0": Strategic opportunity for the development of the italian citrus chain. *Agriculture.* 12, 400. doi: 10.3390/agriculture12030400

Douthwaite, B., and Hoffecker, E. (2017). Towards a complexity-aware theory of change for participatory research programs working within agricultural innovation systems. *Agric. Syst.* 155, 88–102. doi: 10.1016/j.agsy.2017.04.002

El Bilali, H. (2019). Innovation-sustainability nexus in agriculture transition: case of agroecology. *Open Agric.* 4, 1–16. doi: 10.1515/opag-2019-0001

Ermolieva, T., Havlik, P., Frank, S., Kahil, T., Balkovic, J., Skalsky, R., et al. (2022). A risk-informed decision-making framework for climate change adaptation through robust land use and irrigation planning. *Sustainability* 14, 1430. doi: 10.3390/su14031430

Feo, E., Burssens, S., Mareen, H., and Spanoghe, P. (2022a). Shedding light into the need of knowledge sharing in H2020 thematic networks for the agriculture and forestry innovation. *Sustainability* 14, 3951. doi: 10.3390/su14073951

Feo, E., Spanoghe, P., Berckmoes, E., Pascal, E., Mosquera-Losada, R., Opdebeeck, A., et al. (2022b). The multi-actor approach in thematic networks for agriculture and forestry innovation. *Agric. Food Econ.* 10, 3. doi: 10.1186/s40100-021-00209-0

Fernández, J. E., Diaz-Espejo, A., Hernandez-Santana, V., and Cuevas, M., v. (2019). Does precision irrigation help to reduce water consumption in agriculture? *Acta Hortic.* 1253, 199–205. doi: 10.17660/ActaHortic.2019.1253.27

Fieldsend, A. F., Varga, E., Bir,ó, S., von Münchhausen, S., and Häring, A. M. (2022). Multi-actor co-innovation partnerships in agriculture, forestry and related sectors in Europe: Contrasting approaches to implementation. *Agric. Syst.* 202, 103472. doi: 10.1016/j.agsy.2022.103472

Galanakis, C. M., Rizou, M., Aldawoud, T. M. S., Ucak, I., and Rowan, N. J. (2021). Innovations and technology disruptions in the food sector within the COVID-19 pandemic and post-lockdown era. *Trends Food Sci. Technol.* 110, 193–200. doi: 10.1016/j.tifs.2021.02.002

Gambelli, D., Solfanelli, F., Orsini, S., and Zanoli, R. (2021). Measuring the economic performance of small ruminant farms 2 using balanced scorecard and importance-performance analy-sis: a European case study. *Sustainability.* 13, 3321. doi: 10.3390/su13063321

Gao, L., Wang, S., Li, J., and Li, H. (2017). Application of the extended theory of planned behavior to understand individual's energy saving behavior in workplaces. *Resour. Conserv. Recycl.* 127, 107–113. doi: 10.1016/j.resconrec.2017.08.030

Guaitero, B., Saavedra, D. P., Ariza, C., Rugeles, L., and Saavedra, D. (2013). Measuring innovation in agricultural firms: a methodological approach. *Electr. J. Knowl. Manag.* 11, 185.

Gutiérrez, J. A., and Macken-Walsh, Á. (2022). Ecosystems of collaboration for sustainability-oriented innovation: the importance of values in the agri-food value-chain. *Sustainability* 14, 11205. doi: 10.3390/su141811205

Hannus, V., and Sauer, J. (2021). Understanding farmers' intention to use a sustainability standard: The role of economic rewards, knowledge, and ease of use. *Sustainability* 13, 10788. doi: 10.3390/su131910788

Hansson, H., Ferguson, R., and Olofsson, C. (2012). Psychological constructs underlying farmers' decisions to diversify or specialise their businesses - an application of theory of planned behaviour. *J. Agric. Econ.* 63, 465–482. doi: 10.1111/j.1477-9552.2012.00344.x

Harwiki, W., and Malet, C. (2020). Quintuple helix and innovation on performance of SMEs within ability of SMEs as a mediator variable: A comparative study of creative industry in Indonesia and Spain. *Manage. Sci. Lett.* 10, 18. doi: 10.5267/j.msl.2019.11.018

Hashem, M. S., El-Abedin, T. Z., and Al-Ghobari, H. M. (2019). Rational water uses by applying regulated deficit and partial root-zone drying irrigation techniques in tomato under arid conditions. *Chilean J. Agric. Res.* 79, 75–88. doi: 10.4067/S0718-58392019000100075

Hasler, K., Olfs, H. W., Omta, O., and Bröring, S. (2016). Drivers for the adoption of eco-innovations in the German fertilizer supply chain. *Sustainability* 8, 682. doi: 10.3390/su8080682

Hou, J., and Hou, B. (2019). Farmers' adoption of low-carbon agriculture in China: An extended theory of the planned behavior model. *Sustainability* 11, 1399. doi: 10.3390/su11051399

Hsieh, R. M., and Kelley, D. J. (2016). The role of cognition and information access in the recognition of innovative opportunities. *J. Small Bus. Manag.* 54, 297–311. doi: 10.1111/jsbm.12300

Iocola, I., Angevin, F., Bockstaller, C., Catarino, R., Curran, M., Messéan, A., et al. (2020). An actor-oriented multi-criteria assessment framework to support a transition towards sustainable agricultural systems based on crop diversification. *Sustainability* 12, 5434. doi: 10.3390/su12135434

Issa, I., and Hamm, U. (2017). Adoption of organic farming as an opportunity for Syrian farmers of fresh fruit and vegetables: An application of the theory of planned behaviour and structural equation modelling. *Sustainability* 9, 2024. doi: 10.3390/su9112024

Jiménez, A. F., Cárdenas, P. F., and Jiménez, F. (2022). Intelligent IoT-multiagent precision irrigation approach for improving water use efficiency in irrigation systems at farm and district scales. *Comput. Electr. Agric.* 192, 106635. doi: 10.1016/j.compag.2021.106635

Joao, A. R. B., Luzardo, F., and Vanderson, T. X. (2015). An interdisciplinary framework to study farmers decisions on adoption of innovation: Insights from Expected Utility Theory and Theory of Planned Behavior. *African J. Agric. Res.* 10, 2814–2825. doi: 10.5897/AJAR2015.9650

Judge, M., Warren-Myers, G., and Paladino, A. (2019). Using the theory of planned behaviour to predict intentions to purchase sustainable housing. *J. Cleaner Prod.* 215, 259–267. doi: 10.1016/j.jclepro.2019.01.029

Jun, Y., and Kim, K. (2022). Developing an open innovation attitude assessment framework for organizations: focusing on open innovation role perspective and locus of activity. *Behav. Sci.* 12, 46. doi: 10.3390/bs12020046

Kalaitzandonakes, N., Carayannis, E. G., Grigoroudis, E., and Rozakis, S. (2018). Introduction: innovation and technology transfer in agriculture. *Innov. Technol. Knowl. Manag.* 35, 1–10. doi: 10.1007/978-3-319-67958-7_1

Kalinin, A., Teplinsky, I., and Ustroev, A. (2018). Substantiation of tillage methods aimed at rational usage of water resources. *Eng. Rural Develop.* 17, 392–399. doi: 10.22616/ERDev2018.17.N517

Keswani, B., Mohapatra, A. G., Mohanty, A., Khanna, A., Rodrigues, J. J. P. C., Gupta, D., et al. (2019). Adapting weather conditions based IoT enabled smart irrigation technique in precision agriculture mechanisms. *Neural Comput. Applic.* 31, 277–292. doi: 10.1007/s00521-018-3737-1

Khandaker, M., and Kotzen, B. (2018). The potential for combining living wall and vertical farming systems with aquaponics with special emphasis on substrates. *Aquac. Res.* 49, 1454–1468. doi: 10.1111/are.13601

Kim, S. J., Kim, K. H., and Choi, J. (2019). The Role of Design Innovation in Understanding Purchase Behavior of Augmented Products. *J. Bus. Res.* 99, 354–362. doi: 10.1016/j.jbusres.2017.09.047

Klerkx, L., and Begemann, S. (2020). Supporting food systems transformation: The what, why, who, where and how of mission-oriented agricultural innovation systems. *Agric. Syst.* 184, 102901. doi: 10.1016/j.agsy.2020.102901

Klerkx, L., van Mierlo, B., and Leeuwis, C. (2012). "Evolution of systems approaches to agricultural innovation: Concepts, analysis and interventions," in *Farming Systems Research into the 21st Century: The New Dynamic* (Netherlands: Springer) 457–483. doi: 10.1007/978-94-007-4503-2_20

Kourgialas, N. N., Hliaoutakis, A., Argyriou, A., v., Morianou, G., Voulgarakis, A. E., et al. (2022). A web-based GIS platform supporting innovative irrigation management techniques at farm-scale for the Mediterranean island of Crete. *Sci. Total Environ.* 842, 156918. doi: 10.1016/j.scitotenv.2022.156918

Kourgialas, N. N., Koubouris, G. C., and Dokou, Z. (2019). Optimal irrigation planning for addressing current or future water scarcity in Mediterranean tree crops. *Sci. Total Environ.* 654, 616–632. doi: 10.1016/j.scitotenv.2018.11.118

Kubankova, M., Hajek, M., and Votavova, A. (2016). Environmental and social value of agriculture innovation. *Agric. Econ.* 62, 101–112. doi: 10.17221/58/2015-AGRICECON

Kudryashova, E., and Casetti, M. (2021). The Internet of Things - the Nearest Future of Viticulture. *Agris On-Line Papers Econ. Inform.* 13, 79–86. doi: 10.7160/aol.2021.130206

Kukal, M. S., and Irmak, S. (2018). Climate-driven crop yield and yield variability and climate change impacts on the U.S. *Great Plains Agric. Prod.* 8, 1–8. doi: 10.1038/s41598-018-21848-2

Kumar, D. M., Sharma, V., Govindarajo, N. S., and Rahmawati. (2021). Agriculture 4.0 and smart farming: Imperatives of scaling up innovation and farmer capabilities for sustainable business. *Indian J. Ecol.* 48, 1–8.

Lang, Z., and Rabotyagov, S. (2022). Socio-psychological factors influencing intent to adopt conservation practices in the Minnesota River Basin. *J. Environ. Manage.* 307. doi: 10.1016/j.jenvman.2022.114466

Läpple, D., Renwick, A., and Thorne, F. (2015). Measuring and understanding the drivers of agricultural innovation: Evidence from Ireland. *Food Policy* 51, 1–8. doi: 10.1016/j.foodpol.2014.11.003

Liu, J., Hertel, T. W., Lammers, R. B., Prusevich, A., Baldos, U. L. C., Grogan, D. S., et al. (2017). Achieving sustainable irrigation water withdrawals: Global impacts on food security and land use. *Environ. Res. Lett.* 12, 104009. doi: 10.1088/1748-9326/aa88db

Liu, T., Bruins, R. J. F., and Heberling, M. T. (2018). Factors influencing farmers' adoption of best management practices: A review and synthesis. *Sustainability.* 10, 432. doi: 10.3390/su10020432

López-Felices, B., Aznar-Sánchez, J. A., Velasco-Muñoz, J. F., and Piquer-Rodríguez, M. (2020). Contribution of irrigation ponds to the sustainability of agriculture. A review of worldwide research. *Sustainability* 12, 5425. doi: 10.3390/su12135425

Lopriore, G., and Caliandro, A. (2022). Irrigation of intensive olive groves in the Mediterranean environment with different water regimes on two different soils: effects on yields, water use efficiency, vegetative behaviour and water status of the crop. *Acta Hortic.* 1335, 541–548. doi: 10.17660/ActaHortic.2022.1335.68

Loures, L., Chamizo, A., Ferreira, P., Loures, A., Castanho, R., and Panagopoulos, T. (2020). Assessing the effectiveness of precision agriculture management systems in mediterranean small farms. *Sustainability* 12, 3765. doi: 10.3390/su12093765

Maizza, A., Fait, M., Scorrano, P., and Iazzi, A. (2019). How knowledge sharing culture can become a facilitator of the sustainable development in the agrifood sector. *Sustainability* 11, 952. doi: 10.3390/su11040952

Malek, K., Adam, J. C., Stöckle, C. O., and Peters, R. T. (2018). Climate change reduces water availability for agriculture by decreasing non-evaporative irrigation losses. *J. Hydrol.* 561, 444–460. doi: 10.1016/j.jhydrol.2017.11.046

Maru, Y. T. (2018). Summary: Critical reflection on and learning from Agricultural Innovation Systems (AIS) approaches and emerging Agricultural Research. for Development (AR4D) practice. *Agric. Syst.* 165, 354–356. doi: 10.1016/j.agsy.2018.07.012

Masia, S., Sušnik, J., Marras, S., Mereu, S., Spano, D., and Trabucco, A. (2018). Assessment of irrigated agriculture vulnerability under climate change in Southern Italy. *Water* 10, 209. doi: 10.3390/w10020209

Mateos, L., Villalobos, F. J., and Fereres, E. (2016). *Irrigation Systems BT-Principles of Agronomy for Sustainable Agriculture*. Cham: Springer International Publishing 255–267. doi: 10.1007/978-3-319-46116-8_19

Medda, S., Fadda, A., and Mulas, M. (2022). Influence of Climate change on metabolism and biological characteristics in perennial woody fruit crops in the mediterranean environment. *Horticulturae* 8, 273. doi: 10.3390/horticulturae8040273

Mekonnen, D. K., Spielman, D. J., Fonsah, E. G., and Dorfman, J. H. (2015). Innovation systems and technical efficiency in developing-country agriculture. *Agric. Econ.* 46, 689–702. doi: 10.1111/agec.12164

Mesa-Vázquez, E., Velasco-Muñoz, J. F., Aznar-Sánchez, J. A., and López-Felices, B. (2021). Three decades of behavioural economics in agriculture. An overview of global research. *Sustainability* 13, 10244. doi: 10.3390/su131810244

Migliore, G., Schifani, G., Romeo, P., Hashem, S., and Cembalo, L. (2015). Are farmers in alternative food networks social entrepreneurs? Evidence from a Behavioral Approach. *J. Agric. Environ. Ethics* 28, 885–902. doi: 10.1007/s10806-015-9562-y

Mirčetić, V., Ivanović, T., KneŽević, S., Arsić, V. B., Obradović, T., Karabašević, D., et al. (2022). The innovative human resource management framework: impact of green competencies on organisational performance. *Sustainability* 14, 2713. doi: 10.3390/su14052713

Mirzaei, O., Micheels, E. T., Boecker Student, A., and Professor, A. (2016). "Product and Marketing Innovation in Farm-Based Businesses: The Role of Entrepreneurial Orientation and Market Orientation," in *International Food and Agribusiness Management Review* 19.

Montanaro, G., Xiloyannis, C., Nuzzo, V., and Dichio, B. (2017). Orchard management, soil organic carbon and ecosystem services in Mediterranean fruit tree crops. *Scientia Hortic.* 217, 92–101. doi: 10.1016/j.scienta.2017.01.012

Montes de Oca Munguia, O., Pannell, D. J., and Llewellyn, R. (2021). Understanding the adoption of innovations in agriculture: A review of selected conceptual models. *Agronomy* 11, 139. doi: 10.3390/agronomy11010139

Mozzato, D., Gatto, P., Defrancesco, E., Bortolini, L., Pirotti, F., Pisani, E., et al. (2018). The role of factors affecting the adoption of environmentally friendly farming practices: Can geographical context and time explain the differences emerging from literature? *Sustainability* 10, 3101. doi: 10.3390/su10093101

Müller, J., Acevedo-Duque, Á., Müller, S., Kalia, P., and Mehmood, K. (2021). Predictive sustainability model based on the theory of planned behavior incorporating ecological conscience and moral obligation. *Sustainability* 13, 4248. doi: 10.3390/su13084248

Müller, J. M., Buliga, O., and Voigt, K. I. (2018). Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. *Technol. Forec. Soc. Change* 132, 2–17. doi: 10.1016/j.techfore.2017.12.019

Nguyen, T. P. L., Mula, L., Cortignani, R., Seddaiu, G., Dono, G., Virdis, S. G. P., et al. (2016). Perceptions of present and future climate change impacts on water availability for agricultural systems in the western mediterranean region. *Water* 8, 523. doi: 10.3390/w8110523

Niu, G., and Masabni, J. (2021). Roles of indoor vertical farming in sustainable production of horticultural crops. *Acta Hortic.* 1305, 365–373. doi: 10.17660/ActaHortic.2021.1305.48

Nsele, M. K., Fyama, J. N. M., Maréchal, K., and Dogot, T. (2022). Factors influencing the sustained adoption of innovative techniques by urban farmers in lubumbashi, democratic republic of congo. *Agriculture* 12, 1157.12081157 doi: 10.3390/agriculture12081157

Pandya, A. B., and Sharma, P. (2021). Climate Change and its Implications for Irrigation, Drainage and Flood Management. *Irrig. Drainage* 70, 976–978. doi: 10.1002/ird.2651

Pardo, J. J., Domínguez, A., Léllis, B. C., Montoya, F., Tarjuelo, J. M., and Martínez-Romero, A. (2022). Effect of the optimized regulated deficit irrigation methodology on quality, profitability and sustainability of barley in water scarce areas. *Agric. Water Manage.* 266. doi: 10.1016/j.agwat.2022.107573

Parra-López, C., Reina-Usuga, L., Carmona-Torres, C., Sayadi, S., and Klerkx, L. (2021). Digital transformation of the agrifood system: Quantifying the conditioning factors to inform policy planning in the olive sector. *Land Use Policy* 108, 105537. doi: 10.1016/j.landusepol.2021.105537

Pereira, L. S., Paredes, P., Melton, F., Johnson, L., Wang, T., López-Urrea, R., et al. (2020). Prediction of crop coefficients from fraction of ground cover and height. Background and validation using ground and remote sensing data. *Agric. Water Manage.* 241, 106197. doi: 10.1016/j.agwat.2020.106197

Pino, G., Toma, P., Rizzo, C., Miglietta, P. P., Peluso, A. M., and Guido, G. (2017). Determinants of farmers' intention to adopt water saving measures: Evidence from Italy. *Sustainability* 9(1). doi: 10.3390/su9010077

Pinto, T., Vilela, A., and Cosme, F. (2021). "Overview of the recent innovations in vitis products," in *Vitis Products: Composition, Health Benefits and Economic Valorization* 131–178.

Ploll, U., Arato, M., Börner, J., and Hartmann, M. (2022). Sustainable Innovations: A Qualitative Study on Farmers' Perceptions Driving the Diffusion of Beneficial Soil Microbes in Germany and the UK. *Sustainability* 14, 5749. doi: 10.3390/su14105749

Quintero, S., Giraldo, D. P., and Garzon, W. O. (2022). Analysis of the Specialization Patterns of an Agricultural Innovation System: A Case Study on the Banana Production Chain (Colombia). *Sustainability* 14, 8550. doi: 10.3390/su14148550

Rabadán, A., González-Moreno, Á., and Sáez-Martínez, F. J. (2019). Improving firms' performance and sustainability: The case of eco-innovation in the agri-food industry. *Sustainability* 11, 5590. doi: 10.3390/su11205590

Rajapathirana, R. P. J., and Hui, Y. (2018). Relationship between innovation capability, innovation type, and firm performance. *J. Innov. Knowl.* 3, 44–55. doi: 10.1016/j.jik.2017.06.002

Rezaei, R., Mianaji, S., and Ganjloo, A. (2018). Factors affecting farmers' intention to engage in on-farm food safety practices in Iran: Extending the theory of planned behavior. *J. Rural Stud.* 60, 152–166. doi: 10.1016/j.jrurstud.2018.04.005

Rogers, E. M. (1995). Lessons for guidelines from the diffusion of innovations. *Joint Commission J. Quality Improve.* 21, 324–328. doi: 10.1016/S1070-3241(16)30155-9

Rose, D. C., and Chilvers, J. (2018). Agriculture 4.0: Broadening responsible innovation in an era of smart farming. *Front. Sustain. Food Syst.* 2, 87. doi: 10.3389/fsufs.2018.00087

Rouzaneh, D., Yazdanpanah, M., and Jahromi, A. B. (2021). Evaluating micro-irrigation system performance through assessment of farmers' satisfaction: implications for adoption, longevity, and water use efficiency. *Agric. Water Manage.* 246. doi: 10.1016/j.agwat.2020.106655

Saeed, F. H., Al-Khafaji, M. S., and Mahmood Al-Faraj, F. A. (2021). Sensitivity of irrigation water requirement to climate change in arid and semi-arid regions towards sustainable management of water resources. *Sustainability* 13, 13608. doi: 10.3390/su132413608

Saeedi, S. A. W., Juwaidah, S., and Kelly, W. K. S. (2022). Intention to adopt Industry 4.0 technologies among small and medium enterprises in the Malaysian dairy manufacturing industry. *Food Res.* 6, 209–218. doi: 10.26656/fr.2017.6(2).211

Sarkar, A., Wang, H., Rahman, A., Abdul Azim, J., Hussain Memon, W., and Qian, L. (2022). Structural equation model of young farmers' intention to adopt sustainable agriculture: a case study in Bangladesh. *Renew. Agric. Food Syst.* 37, 142–154. doi: 10.1017/S1742170521000429

Sarri, D., Lisci, R., Rimediotti, M., Vieri, M., and Storchi, P. (2015). "Applications of the precision viticulture techniques in the Chianti district," in *1st Conference on Proximal Sensing Supporting Precision Agriculture - Held at Near Surface Geoscience* 121–125. doi: 10.3997/2214-4609.201413851

Schaltegger, S., and Wagner, M. (2011). Sustainable entrepreneurship and sustainability innovation: Categories and interactions. *Bus. Strat. Environ.* 20, 222–237. doi: 10.1002/bse.682

Senger, I., Borges, J. A. R., and Machado, J. A. D. (2017). Using the theory of planned behavior to understand the intention of small farmers in diversifying their agricultural production. *J. Rural Stud.* 49, 32–40. doi: 10.1016/j.jrurstud.2016.10.006

Sgroi, F., Candela, M., di Trapani, A. M., Foder,à, M., Squatrito, R., Testa, R., et al. (2015). Economic and financial comparison between organic and conventional farming in Sicilian lemon orchards. *Sustainability* 7, 947–961. doi: 10.3390/su7010947

Shi, J., Wu, X., Zhang, M., Wang, X., Zuo, Q., Wu, X., et al. (2021). Numerically scheduling plant water deficit index-based smart irrigation to optimize crop yield and water use efficiency. *Agric. Water Manage.* 248, 106774. doi: 10.1016/j.agwat.2021.106774

Shi, J., Zhang, J., Xie, N., Yang, Z., and Luo, J. (2022). An agricultural supply chain coordination model: the case of trinity comprehensive cooperation organization in China. *Sustainability* 14, 8879. doi: 10.3390/su14148879

Silva, L. L., Barbosa, C., Fitas Da Cruz, V., Sousa, A., Silva, R., Lourenço, P., et al. (2022). How could precision irrigation based on daily trunk growth improve super high-density olive orchard irrigation efficiency? *Agronomy.* 12, 756. doi: 10.3390/agronomy12040756

Sivertsson, O., and Tell, J. (2015). Barriers to business model innovation in Swedish agriculture. *Sustainability* 7, 1957–1969. doi: 10.3390/su7021957

Small, B., and Maseyk, F. J. F. (2022). Understanding farmer behaviour: A psychological approach to encouraging pro-biodiversity actions on-farm. *New Zealand J. Ecol.* 46, 20. doi: 10.20417/nzjecol.46.20

Sok, J., Borges, J. R., Schmidt, P., and Ajzen, I. (2021). Farmer Behaviour as Reasoned Action: A Critical Review of Research with the Theory of Planned Behaviour. *J. Agric. Econ.* 72, 388–412. doi: 10.1111/1477-9552.12408

Soorani, F., and Ahmadvand, M. (2019). Determinants of consumers' food management behavior: Applying and extending the theory of planned behavior. *Waste Manag.* 98, 151–159. doi: 10.1016/j.wasman.2019.08.025

Souza, S. A., and Rodrigues, L. N. (2022). Increased profitability and energy savings potential with the use of precision irrigation. *Agric. Water Manage.* 270, 107730. doi: 10.1016/j.agwat.2022.107730

Spendrup, S., and Fernqvist, F. (2019). Innovation in agri-food systems – a systematic mapping of the literature. *Int. J. Food Syst. Dyn.* 10, 402–427.

Sulistyo, H., and Ayuni, S. (2020). Competitive advantages of SMEs: The roles of innovation capability, entrepreneurial orientation, and social capital. *Contaduria y Admin.* 65, 1983. doi: 10.22201/fca.24488410e.2020.1983

Takács-György, K., and Takács, I. (2022). Towards climate smart agriculture: How does innovation meet sustainability? *Ecocycles* 8, 61–72. doi: 10.19040/ecocycles.v8i1.220

Tama, R. A. Z., Ying, L., Yu, M., Hoque, M. M., Adnan, K. M., and Sarker, S. A. (2021). Assessing farmers' intention towards conservation agriculture by using the Extended Theory of Planned Behavior. *J. Environ. Manage.* 280. doi: 10.1016/j.jenvman.2020.111654

Testa, R., Foderà, M., di Trapani, A. M., Tudisca, S., and Sgroi, F. (2015). Choice between alternative investments in agriculture: The role of organic farming to avoid the abandonment of rural areas. *Ecol. Eng.* 83, 227–232. doi: 10.1016/j.ecoleng.2015.06.021

Tong, X., Wu, P., Liu, X., Zhang, L., Zhou, W., and Wang, Z. (2022). A global meta-analysis of fruit tree yield and water use efficiency under deficit irrigation. *Agric. Water Manage.* 260, 107321. doi: 10.1016/j.agwat.2021.107321

Tóth, J., Migliore, G., Balogh, J. M., and Rizzo, G. (2020). Exploring innovation adoption behavior for sustainable development: The case of Hungarian food sector. *Agronomy* 10, 612. doi: 10.3390/agronomy10040612

Turral, H., Svendsen, M., and Faures, J. M. (2010). Investing in irrigation: Reviewing the past and looking to the future. *Agric. Water Manage.* 97, 551–560. doi: 10.1016/j.agwat.2009.07.012

Ungureanu, N., Vlăduţ, V., and Voicu, G. (2020). Water scarcity and wastewater reuse in crop irrigation. *Sustainability* 12, 55. doi: 10.3390/su12219055

Unsworth, K., Sawang, S., Murray, J., Norman, P., and Sorbello, T. (2012). Understanding innovation adoption: Effects of orientation, pressure and control on adoption intentions. *Int. J. Innov. Manage.* 16, 3593. doi: 10.1142/S1363919611003593

van Dijk, W. F. A., Lokhorst, A. M., Berendse, F., and de Snoo, G. R. (2016). Factors underlying farmers' intentions to perform unsubsidised agri-environmental measures. *Land Use Policy* 59, 207–216. doi: 10.1016/j.landusepol.2016.09.003

van Gerrewey, T., Boon, N., and Geelen, D. (2022). Vertical farming: The only way is up? *Agronomy* 12, 2. doi: 10.3390/agronomy12010002

van Loo, E. J., Caputo, V., and Lusk, J. L. (2020). Consumer preferences for farm-raised meat, lab-grown meat, and plant-based meat alternatives: Does information or brand matter? *Food Policy* 95. 1931. doi: 10.1016/j.foodpol.2020.101931

Velasco-Muñoz, J. F., Aznar-Sánchez, J. A., Batlles-delaFuente, A., and Fidelibus, M. D. (2019). Sustainable irrigation in agriculture: An analysis of global research. *Water* 11, 1758. doi: 10.3390/w11091758

Wang, Y., Wang, Y., and Fan, P. (2022). Analysis of Micro Value Flows in the Value Chain of Eco-Innovation in Agricultural Products. *Sustainability* 14. 7971. doi: 10.3390/su14137971

Wauters, E., Bielders, C., Poesen, J., Govers, G., and Mathijs, E. (2010). Adoption of soil conservation practices in Belgium: An examination of the theory of planned behaviour in the agri-environmental domain. *Land Use Policy* 27, 86–94. doi: 10.1016/j.landusepol.2009.02.009

Wolf, S., Just, D., and Zilberman, D. (2001). Between data and decisions: the organization of agricultural economic information systems. *Res. Policy* 30, 121–141.

Yan, L., Zhao, X., Zhang, D., Deng, J., and Zhang, Y. (2022). Associated factors of pesticide packaging waste recycling behavior based on the theory of planned behavior in Chinese fruit farmers. *Sustainability* 14, 10937. doi: 10.3390/su141710937

Yildirim, T., Zhou, Y., Flynn, K. C., Gowda, P. H., Ma, S., and Moriasi, D. N. (2021). Evaluating the sensitivity of vegetation and water indices to monitor drought for three Mediterranean crops. *Agron. J.* 113, 123–134. doi: 10.1002/agj2.20475

Zagaria, C., Schulp, C. J. E., Zavalloni, M., Viaggi, D., and Verburg, P. H. (2021). Modelling transformational adaptation to climate change among crop farming systems in Romagna, Italy. *Agric. Syst.* 188. doi: 10.1016/j.agsy.2020.1 03024

Zaporozhchenko, V., Tkachuk, A., Tkachuk, T., and Dotsenko, V. (2022). The evaluation of irrigating meliorations efficiency after the change of climatic conditions. *J. Water Land Develop.* 52, 199–204. doi: 10.24425/jwld.2022.140390

Zhang, D., Xie, X., Wang, T., Wang, B., and Pei, S. (2022). Research on water resources allocation system based on rational utilization of brackish water. *Water* 14, 948. doi: 10.3390/w14060948

Zhang, K. (2018). Theory of planned behavior: Origins, development and future direction. *Int. J. Human. Soc. Sci. Invent.* 7, 76–83.

Zhang, Q., Xiao, H., Duan, M., Zhang, X., and Yu, Z. (2015). Farmers' attitudes towards the introduction of agri-environmental measures in agricultural infrastructure projects in China: Evidence from Beijing and Changsha. *Land Use Policy* 49, 92–103. doi: 10.1016/j.landusepol.2015.0 7.021

Zhu, J., Xu, N., Siddique, K. H. M., Zhang, Z., and Niu, W. (2022). Aerated drip irrigation improves water and nitrogen uptake efficiencies of tomato roots with associated changes in the antioxidant system. *Scien. Hortic.* 306, 471. doi: 10.1016/j.scienta.2022.111471

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 08 March 2023
DOI 10.3389/fsufs.2023.1128103

Check for updates

OPEN ACCESS

EDITED BY
Marzia Ingrassia,
Università degli Studi di Palermo, Italy

REVIEWED BY
Luigi Liotta,
University of Messina, Italy
Marian Butu,
National Institute of Research and Development for Biological Sciences (NIRDBS), Romania

*CORRESPONDENCE
Roberta Selvaggi
✉ roberta.selvaggi@unict.it

SPECIALTY SECTION
This article was submitted to Waste Management in Agroecosystems, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 20 December 2022
ACCEPTED 13 February 2023
PUBLISHED 08 March 2023

CITATION
Castellano A, Selvaggi R, Mantovi P, Spina D, Hamam M and Pappalardo G (2023) The effect of fertilization with microfiltered liquid digestate on the quality parameters of Citrus fruits. *Front. Sustain. Food Syst.* 7:1128103.
doi: 10.3389/fsufs.2023.1128103

The effect of fertilization with microfiltered liquid digestate on the quality parameters of Citrus fruits

Angela Castellano[1], Roberta Selvaggi[2]*, Paolo Mantovi[3], Daniela Spina[2], Manal Hamam[2] and Gioacchino Pappalardo[2]

[1]Mediterranean Nutraceutical Extracts (Medinutrex) srls, Catania, Italy, [2]Department of Agriculture, Food and Environment, University of Catania, Catania, Italy, [3]Centro Ricerche Produzioni Animali (CRPA) SpA, Reggio Emilia, Italy

Nowadays, the adoption of sustainable agricultural practices, including the reduction of synthetic fertilizers, has become a challenge for the agriculture sector. In this experimental work, the effect of the liquid fraction of digestate (by-product of the anaerobic digestion process) as a fertilizer was evaluated. The aim of the research was to verify to which extent digestate can affect growth and quality parameters of orange fruits, comparing the results to those obtained for fruits grown on soil treated with conventional mineral fertilizers. To assess the effectiveness of the treatments, different qualitative and quantitative parameters of Citrus fruits were measured. In particular, the results showed slight differences between the two treatments, suggesting that digestate may be used for the production of high-quality fruits. Moreover, in some orchards, the Citrus fruits of the plants treated with digestate showed a higher concentration of health-promoting compounds, such as vitamin C, flavonoids, phenolic content, when compared to the control group. Thus, digestate can be considered an optimal source of plant nutrients and can be used as a crop growth promoter, since it represents an effective strategy for reducing the mineral fertilizers input.

KEYWORDS

digestate, orange juice, fertilization, HPLC, flavonoids, ascorbic acid

1. Introduction

The genus Citrus, native to subtropical Asia, belongs to the subfamily Aurantioideae and order of Sapindales of the Rutaceae family (Agouillal et al., 2017). Nowadays, citrus make up the largest sector of the world's fruit production with more than 100 million tons produced every year (Li et al., 2006). Citrus fruits are a great source of naturally occurring nutrients, such as sugars, organic acids, vitamin C and flavonoids, which only in recent years, have attracted increasing attention thanks to their nutritional and beneficial effects on human health (Turner and Burri, 2013). Among all citrus crops, oranges account for more than half of world citrus production and are the most widely traded fruits, followed by mandarins, limes and lemons and grapefruits (Food Agriculture Organization, 2017). In Europe, Italy is the second orange producer after Spain. Italian orange production is concentrated in the Mediterranean area, in particular in Sicily and Calabria, whose production accounts for ~63 and 19% of the total national production, respectively (Bettini, 2018). As a perennial evergreen tree, citrus requires water and nutrients throughout the year for higher orchard efficiency (Davies and Albrigo, 1994). The quality of Citrus fruits is influenced by several factors, among which fertilization plays a key role. Growers can modulate fruit quality development with modifications of the cationic (K, Ca, and Mg) or anionic (N, P, and S) composition of the soil solution. In the last century, the increasing growth of world population, followed by a higher demand for food, has led farmers to rely almost exclusively on synthetic mineral fertilizers. The advantages of these chemicals are unquestionable, since they can boost crop production, allowing farmers to grow more food on less land. On the other hand, synthetic mineral fertilizers are responsible of many environmental issues, contributing for instance to the eutrophication of freshwater systems and coastal areas and causing pollution of soil, groundwater and air (Lado et al., 2018).

In this context, to reverse the trend of massive use of synthetic fertilizers, the role of the digestate can be very important. It is an organic soil improver obtained at the end of the anaerobic digestion process. Digestate is rich in stable organic matter and fertility elements such as nitrogen, phosphorus and potassium, and for this reason it can be used as fertilizer on major agricultural crops (Pappalardo et al., 2018; Giuseppe et al., 2020). This substrate, compared to the initial biomass fed into anaerobic digestion plants, is more homogeneous and has a higher moisture content. This happens as a consequence of the dry matter biological degradation operated by the bacteria contained in the digesters, which are responsible for biogas production (Nkoa, 2014). Moreover, digestate retains the main fertility elements (macro and virtually all meso- and trace elements) together with the portion of the less degradable organic carbon that has not been converted into methane or CO_2; for this reason, it is more stable when it returns to the soil (Hans and Eder, 2013). In fact, anaerobic digestion results into a reduction of less stable organic matter, but does not decrease the nitrogen, phosphorus and potassium supply of the initial biomass (Valenti et al., 2018, 2020).

The use of digestate as fertilizer represents an important agronomic strategy not only because of the presence of fertility elements but also because of the possibility to close the carbon and nutrient cycles. The latter figures among the key principles of sustainable agriculture which brings back the centrality of matter recovery as a means of sustaining agricultural production (Murano et al., 2021; Pappalardo et al., 2022). In the last years, the effects of digestate on soil quality have been widely investigated (Alburquerque et al., 2012; Muscolo et al., 2017; Doyeni et al., 2021), bringing considerable socio-economic and environmental benefits for all the agricultural system. But, to the best of our knowledge, only few experimental works (Morra et al., 2021; Panuccio et al., 2021) have investigated how it can affect fruit quality for pluriannual crops. So, we set up an experiment to measure how much the usage of digestate can affect the quality parameters of citrus fruits.

Ascorbic acid, total phenols, flavonoids and other physicochemical parameters of citrus treated with digestate were compared to those obtained for fruits treated with conventional mineral fertilizers, in the same farm.

To this purpose, orange fruits (Citrus sinensis, cv Washington Navel and Tarocco Scirè) were collected in three different farms located in Sicily. For each farm we have distinguished two adjacent fields. All the cultivation conditions were the same, but we changed the fertilizers used: in the experimental field, only digestate was spread for the yearly fertilization; while, in the conventional one, only synthetic fertilizers were used.

Then, the fresh squeezed citrus juices obtained by the different field were analyzed to determine physicochemical and antioxidant parameters, such as the content of ascorbic acid, total phenolics, flavonoids and others. It is important to underline that the comparison of fruit quality parameters was made on citrus collected in the same farm, meaning that the statistical analysis regards those differences determined by the treatment (conventional or digestate) only.

2. Technical information on microfiltered digestate

It is well-known that the use of biomass for agro-energy purposes leads, through the anaerobic digestion process, to the production of biogas. It is much less known, however, that digestate is the by-product of this anaerobic digestion process and it is a product that contains the main elements of soil fertility, making it suitable as a fertilizer on the main agricultural crops.

The agronomic use of digestate as fertilizer is important for the contribution of fertility elements to replace synthetic fertilizers. It is also important for the possibility of closing the carbon and nutrients cycle which are key factors for understanding a sustainable agriculture based on the recovery and the reuse of waste from the production process (Jin et al., 2022).

After the digestate production process in biogas plants, usually, its mechanical separation is carried out. This phase allows above all to obtain two fractions of the digestate: a liquid one called clarified or "pumpable" and a solid one called solid or "palable" (Giuseppe et al., 2020). This separation is due both to a greater efficiency in managing the digestate at company level and to its agronomic uses.

The two fractions generated from the separation process have a very distinct fertilizing power. The solid fraction is called "palable" because of its dry matter content higher than 20% that gives it greater consistency. It presents nitrogen in organic form and a nitrogen / phosphorus ratio shifted in favor of phosphorus (Peng et al., 2020). It has a greater amount of organic matter than the liquid fraction. In the agronomic field it is the most suitable fraction to be used as a soil improver and it represents a valid substitute for manure, helping to maintain the soil's organic matter supply. This fraction can be used whenever a slow-acting organic fertilizer is needed, capable of slowly transferring the nutrients to the soil (Zeng et al., 2022).

The liquid fraction is "pumpable" because it has a low amount of dry matter. It has a lower amount of organic matter and a higher content of nitrogen in the ammoniacal form, which can represent up to 70–90% of the total nitrogen and a nitrogen/phosphorus ratio shifted in favor of nitrogen (Peng et al., 2020). It is a ready-to-use fertilizer, capable of quickly releasing nutrients to crops. Moreover, thanks to the significant ease of infiltration into the soil immediately after the spreading, the distribution of the liquid fraction of the digestate can reduce ammonia emissions into the atmosphere with a shallow burial (Möller, 2015). The burial technique also reduces the odor impact caused by the digestate injection, avoiding annoyance to local inhabitants (Orzi et al., 2018).

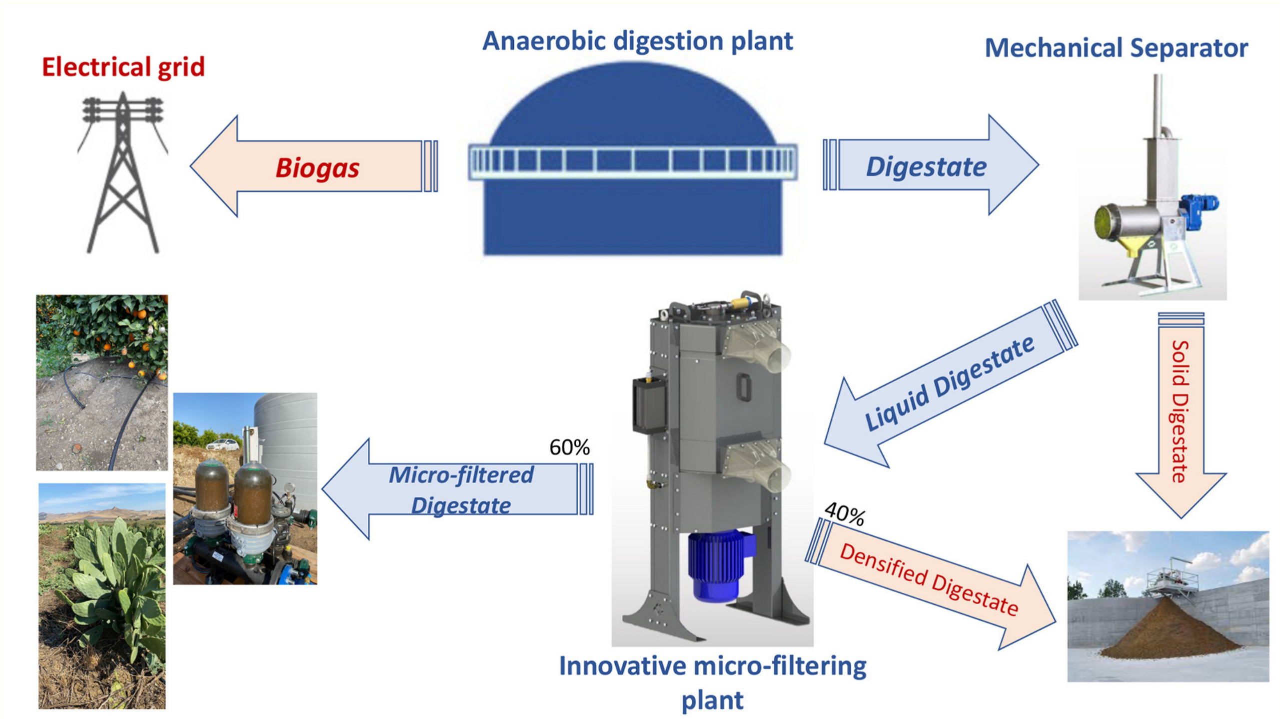


FIGURE 1
Micro-filtered digestate production process.

Alongside the aforementioned traditional forms of digestate, in this paper we have considered a further innovative form of digestate known as "microfiltered digestate." As shown in Figure 1, the microfiltered digestate is obtained from the liquid digestate fraction, subjected to a micro-filtration process within an innovative plant known as a "micro-filter."

It is a mechanical separation of the liquid fraction, without any pre-treatment.

The innovative experimental microfiltration plant shown in Figure 1 allows to obtain a microfiltered liquid phase that can be used in fertigation with driplines, ensuring the maximum use efficiency of nutrients and water contained in it. The microfilter allows, in fact, to exclude from the microfiltered phase the particles larger than 50 microns which could occlude the drip labyrinths of the dripline system (Manetto et al., 2022).

In this experimental condition, the microfiltered digestate represents about 60% of the liquid digestate inside the microfilter and retains, on average, 1.5–8% dry matter. Within this solution there are many chemical compounds useful for crop fertilization, the most important of which is undoubtedly nitrogen in ammoniacal form, in the percentage of 70–90% of the total dissolved nitrogen.

Microfiltered digestate is produced in order to provide it in fertigation on permanent crops (e.g., citrus, olive trees, vines, and forage opuntia) with a dripline system, after to be stored in tanks near the fertigation site.

Currently, fertigation with digestate mixed with irrigation water is a practice not yet widespread. That is because the chemical-physical characteristics of the digestate, even if already clarified with the solid-liquid separation treatment, cause clogging problems of the dispensers with considerable worsening of the quality and efficiency of the overall operation.

The densified fraction obtained after the innovative micro-filtration is semi-solid, with a relatively high dry matter content, usually above about 20 percent. Usually, this fraction is mixed to the liquid pumpable fraction of the digestate.

The best way to use this microfiltered fraction consists in the distribution systems that temporally allow the contributions to coincide as much as possible with the demands of the crops, maximizing the use efficiency of nutrients and water.

Typically, in Mediterranean area, digestate is uncompetitive with chemical fertilizers because it is scattered throughout the territory, resulting in huge efforts to collect and transport them. The principal barrier to logistic chain is its transportation cost and not its chemical characteristics. Maximum travel distances are highly variable and are strongly dependent on the logistic solution adopted.

In addition, the digestate microfiltration can be the key factor for: (a) optimizing the management of the digestate, expanding its calendar and the possibility of spreading; (b) enhancing in a "particular way" the liquid fraction of the digestate while reducing the use of mineral fertilizers; (c) reducing the problems related to the emissions of odors, ammonia, greenhouse gases, the loss of nitrates to the water (maximizing the efficiency of the use of nutrients); (d) reducing the incidence of transportation costs as it is used in high-income perennial crops.

TABLE 1 Physicochemical composition of the liquid microfilterd digestate used as fertilizer.

TS (g/kg)	VS (g/kg)	TKN (mg/kg)	N-NH_4^+ (mg/kg)	P tot (mg/kg)	K tot (mg/kg)	TSS (g/L)
53.7	27.6	6,266	4,219	846	4,542	40.4

TS, total solids; VS, volatile solids; TKN, total kjeldahl nitrogen; N-NH_4^+, ammonium nitrogen; P tot, total phosphorous; K tot, total potassium; TSS, total suspended solids.

3. Materials and methods

3.1. Experimental design

From March to October, the study was carried out in three different citrus orchards, situated in Eastern Sicily (Italy). Two treatments were compared: (1) plant fertilization managed according to the conventional mineral fertilization applied in the orchard (Control) and (2) plant fertilization based on the microfiltered liquid fraction of digestate. Both experimental and conventional plots were 1 hectare wide each.

The digestate used in this experimental study derives from anaerobic fermentation of mixed agricultural biomasses. Specifically, the biomass mix fed into the anaerobic fermenters consists of 50 percent livestock effluent (poultry manure, chicken manure, cattle manure and cattle slurry), 10 percent triticale silage, 5 percent whey, 20 percent pulp and 15 percent olive pomace and vegetable water. Thus, it is a typical diet in the Mediterranean area where many by-products of agricultural and agro-industrial supply chains are available for energetical purposes.

After a solid-liquid separation process, the clarified portion of the digestate was selected. Before being applied in the orchards, through drip irrigation, the liquid underwent a microfiltration step by means of an innovative SEPCOM microfilter already tested for this scope (Mantovi et al., 2020). The physicochemical characteristics of the microfiltered digestate used as fertilizer are reported in Table 1.

The experimental activity was carried out in three orchards of Citrus sinensis, involved in an European Union-funded research project. To date, there are no other fields employing microfiltered digestate on permanent crops, because this is a copyrighted technology not yet developed.

In farm 1 and farm 3, a common variety of orange (cv Washington Navel) was cultivated, while in Farm 2 a pigmented variety (cv Tarocco Scirè) was harvested. The age of the citrus groves under study varied among the case studies. In farm 1 there are trees of about 28 years old, in farm 2 there are 12-year-old trees, and farm 3 is characterized by younger trees (about 5 years old). It has to be noted that all plots, prior to the use of digestate, used to be fertilized with synthetic fertilizers following a fertilization plan in which we substituted digestate according to nitrogen content.

Table 2 shows the fertilization plan followed for each orchard. The substitution of traditional chemical fertilizers with digestate was studied for each farm separately, considering all the typical individual orchards conditions (age of the plants, cultivar, number of plants per hectare, and others).

Fruits were harvested in the period between January and April 2022, when the commercial size and optimal parameters were reached. In order to represent the studied field adequately, the hectare (sample plot) was divided into 5 subplots and, from each of them, 25 mature fruits were harvested. From a total of 125 fruits, 25 citrus were randomly selected. Fruits were immediately stored at 4°C and, few days later, hand squeezed for the determination of physicochemical and nutraceutical parameters.

The results were obtained by comparing the data pertaining to fruits harvested in the control field (conventional fertilization) and the experimental field (digestate fertilization), within the same farm. This means that the trees, belonging to the same farm, have the same characteristics when it comes to variety, age, and cultivation techniques.

3.2. Chemicals and instrumentation

Folin–Ciocalteu reagent (FCR), sodium carbonate (Na_2CO_3), DMSO and meta-phosphoric acid were purchased from Carlo Erba Reagents (Italy); gallic acid and hesperidin were purchased from Glentham Life Science (United Kingdom), ethanol, hydrochloric acid, sodium hydroxide, L-ascorbic acid, sodium fluoride (NaF) and 6-hydroxy-2,5,7,8-tetramethylchromane-2-carboxylic acid (Trolox) were purchased from Sigma Aldrich (Milan, Italy). HPLC–MS grade solvents (Carlo Erba Chemicals, Italy) were used for chromatography and all other reagents were of analytical grade.

3.3. Determination of physico-chemical parameters

3.3.1. Color

The color of the peel as well as the pulp of the fruits was measured using a precision colorimeter (NR60CP, Shenzhen 3nH Technology Co, LTD, China) based on the CIELAB color space represented by L*, a*, b*, c* and hue values (Giuseppe et al., 2020). Measurements were taken at two different points on equatorial area of each fruit.

3.3.2. Juice yield

For the determination of juice yield, 25 fruits were analyzed. An analytical scale was used to weight both the whole fruits and then the residual peels, obtained after the hand squeezing.

The percentage of juice content was calculated by dividing the difference of total weight and peel weight by the total fruit weight. By multiplying this number by 100, it was possible to get the percentage.

3.3.3. Total soluble solids

The total soluble solids content was measured through a digital refractometer (ATAGO RX-5000). The determination was carried out by placing a fruit juice drop in the sample area of

TABLE 2 Fertigation plans with traditional chemical fertilizers.

	Chemical fertilizer	Nitrogen		Phosphorous		Potassium	
	kg/ha*	Content (%)	kg/ha*	Content (%)	kg/ha*	Content (%)	kg/ha*
Farm 1							
April	400	9.0	36.0	1.0	4.0	5.0	20.0
June	600	9.0	54.0	1.0	6.0	5.0	30.0
September	600	9.0	54.0	1.0	6.0	5.0	30.0
Total			144.0		16.0		80.0
*400 plants per hectare.							
Farm 2							
February	18.15	40.0	7.3				
March	330	30.0	99.0				
April	264					25.0	66.0
April**	54.12	13.0	7.0			46.0	24.9
May	165			54.0	89.1		
May**	18.15	10.5	1.9				
June	330	30.0	99.0				
June**	54.12	13.0	7.0			46.0	24.9
July	99			54.0	53.5		
Total			221.2		142.6		115.8
*330 plants per hectare. **Foliar treatment of fertigation (not substituted by digestate).							
Farm 3							
March	500	9.0	45.0	1.0	5.0	1.0	5.0
April	50	3.0	1.5			25.0	8.3
April**	250	5.0	12.5	2.0	5.0	2.0	5.0
May**	250	5.0	12.5	2.0	5.0	2.0	5.0
June	500	6.0	30.0	2.0	10.0	1.0	5.0
June	50	5.2	2.6				
September**	250	5.0	12.5	2.0	5.0	2.0	5.0
September	100					52.0	52.0
October	500	5.0	25.0	2.0	10.0	1.3	6.5
Total			141.6		40.0		91.8

*500 plants per hectare.
**Foliar treatment of fertigation (not substituted by digestate).

the refractometer to obtain the values of the °Brix concentration readable on the display. The observed Brix degree was then corrected for temperature using the appropriate scale (Kimball, 1991).

3.3.4. pH and total titratable acidity

The pH value was measured with a pH meter (pH700, EUTECH Instruments). Prior to the analysis, the pH electrode was calibrated using technical buffers (pH = 4.00 and pH = 7.00). The electrode was dipped into the samples and rinsed with distilled water before proceeding from one solution to the other. The values appeared on the display unit of the instrument were recorded only one stabilized in order to ensure accuracy. TA was measured by titration of 1 g of juice, diluted with distilled water, with NaOH 0.1 M, using phenolphthalein as indicator. The result was expressed as percentage of citric acid (Kimball, 1991).

3.4. Evaluation of antioxidant compounds and antioxidant activity

3.4.1. Ascorbic acid

The quantification of Vitamin C in orange juice was performed by means of HPLC analysis (Shimadzu Prominence L2C-20AD and SPD-20A) (Rapisarda and Intelisano, 1996). Prior to the determination of the ascorbic acid, the pulp was centrifugated at

15,000 rpm for 30 min at a temperature comprised between 4 and 10°C. The supernatant was filtered using Miracloth paper and 5 mL of this solution were diluted to 50 mL with a 3% solution of metaphosphoric acid. After passing through a 0.45 μm PTFE membrane filter, 20 μL of the sample were injected into the HPLC instrument. For the analysis, a RP-C18 Luna (Phenomenex, 4.6 × 250 mm) column, kept at 30°C, was used. A solution of ortophosphoric acid 0.02 M was used as mobile phase and the flow rate was 1 mL/min. The photodiode array detector was set at 260 nm. The results were expressed as mg of ascorbic acid on 100 mL of juice, by a calibration curve derived from solutions at different concentrations of ascorbic acid.

3.4.2. Total phenolic content

The total phenolic content was evaluated using the Folin–Ciocalteu assay (Singleton et al., 1999). The juice was centrifugated at 15,000 rpm (IEC CL10 Centrifuge, Thermoscientific) for 30 min at a temperature comprised between 4 and 10°C. The supernatant was filtered by using Miracloth paper and 500 μL of the latter were diluted to 10 mL with distilled water. Then, 1 mL of the aqueous solution was added in a flask, together with 5 mL of 10% Folin-Ciocolteau reagent. After 5 min, the mixture was filled up with a solution of Na_2CO_3 (7.5% w/v), agitated and stored in a dark place for 2 h. Afterward, the absorbance was measured at 765 nm using a spectrophotometer (Shimadzu UV-1800). The results were expressed as mg of gallic acid equivalents on L of juice, by a calibration curve.

3.4.3. Flavonoids

For the measurement of the phenolic compounds typical of sweet oranges, i.e., narirutin, hesperidin and didymin, the juice was pre-treated as follows: 10 mL of the flesh were centrifuged with 3,000 rpm for 5 min at 4°C (IEC CL10 Centrifuge, Thermoscientific). Then, 5 mL of the supernatant were diluted to 10 mL with DMSO. Afterwards, 1 mL of the solution was re-diluted with Mobile Phase A (HPLC water+ 0.3% formic acid). Finally, this solution was filtered with a 0.45 μm PTFE membrane filter and injected into the HPLC instrument.

HPLC analyses were carried out by means of Shimadzu Prominence LC-20AD and SPD-20A system, consisting of a quaternary pump, a column temperature control oven and a photodiode array detector. 20 μL of sample were injected into the RP-C18 Luna (Phenomenex, 4.6 × 250 mm) column. The column was kept at 30°C and the flow rate was 1 mL/min. The photodiode array detector was set at 280 nm. A binary gradient composed of water containing 0.3% of formic acid (PHASE A) and acetonitrile containing 0.3% of formic acid (Phase B) was used for the separation. The gradient elution was determined as follows: 0 min: 5% B; 10 min: 20% B; 50 min: 28% B; 60 min: 43% B; 70 min, isocratic for 5 min, followed by re-equilibrating the column to initial conditions (Amenta et al., 2015).

Quantification of phenolic compounds was carried out at 280 nm using external standard method. The phenolic compounds were identified by comparing the retention times with those of the corresponding standards. Calibration curves were obtained using the commercial standard of hesperidin, showing regression coefficients (R2) above 0.999. The results are expressed as mg of hesperidin on L of juice.

3.4.4. Anthocyanins

The anthocyanins content in the orange juice was determined through a spectrophotometer method: 2.5 mL of juice were diluted to 25 mL using a mixture of 95% ethanol and 37% HCl. After the centrifugation of the solution at 3,000 rpm for 5 min, absorbance of the mixture was measured at 535 nm (Shimadzu UV-1800) (Di Giacomo et al., 1989). The results are expressed as mg of cyanidin 3-glucoside on L of juice.

3.4.5. ORAC assay

For the determination of the antioxidant activity of orange juices, the oxygen radical absorbance capacity (ORAC) assay was performed using a Spectrofluorimeter (Perkin Elmer Wallac 1420). The assay (Nagy et al., 1977) consisted in the initial extraction of the lyophilised test samples (0.5 g) at ambient temperature with 25 mL of 80% methanol containing 2 mmol/L NaF for 4 h under stirring and away from light. All samples were dissolved in phosphate buffer solution (pH 7.4). The results are recorded as micromoles of Trolox equivalents per g of dry weight (μmol TE/g DW).

3.4.6. Statistical analysis

All measurements were repeated three times and the values of the data are expressed as arithmetic mean ± standard deviation. One-way analysis of variance (ANOVA) has been performed, and Tukey's test was run to assess the significance of the differences between samples and control samples. A p-value < 0.05 is considered statistically significant.

4. Results

The physicochemical and nutraceutical parameters of citrus harvested in the three different orchards are presented in Table 3. Data are grouped according to the fertilization regime (Control with chemical fertilizers vs. Digestate). Moreover, the results of ORAC assay are reported in a graph (Figure 2).

With regards to Farm 1, results showed that the treatment of the soil with digestate increased the juice yield as well as the titratable acidity. On the contrary, the total soluble solids were higher in the juice obtained from citrus conventionally fertilized (15.31° Brix vs. 12.26° Brix). Moreover, it can be observed that the content of ascorbic acid and flavanones in the juice, both determined by HPLC analysis, was negatively affected by the use of digestate as soil amendment (71.12 vs. 64.11 mg/100 mL and 434.3 vs. 269.6 mg/L, respectively).

The same trend can be observed for total polyphenols, determined using the Folin-Ciocalteau assay, whose values were 89.3 mg/L for the juice treated with liquid digestate and 103.6 mg/L for the flesh derived from conventional treatment, respectively.

Finally, no significant pH variations were observed when conventional fertilizers and digestate were used as amendments.

10.3389/fsufs.2023.1128103

TABLE 3 Physicochemical parameters, bioactive compounds concentration and antioxidant activity evaluated in *Citrus sinensis* varieties.

Parameters	Farm 1		Farm 2				Farm 3			
	Single harverst		First harverst		Second harverst		First harverst		Second harverst	
	Control	Digestate	Control	Digestate	Control	Digestate	Control	Digestate	Control	Digestate
Juice yield (%)	42.21 ± 8.35	47.41 ± 0.85	50.96 ± 0.57	54.69 ± 5.22	58.32 ± 1.80**A**	55.30 ± 1.99**B**	53.88 ± 0.44 **A**	46.07 ± 1.31**B**	47.43 ± 2.02**A**	35.92 ± 1.31**B**
L∗ peel	60.69 ± 0.65	62.18 ± 0.63	65.91 ± 0.26	63.56 ± 1.03	62.45 ± 0.23	62.34 ± 0.97	65.91 ± 0.26	64.96 ± 0.68	61.74 ± 1.51	62.89 ± 1.28
a∗ peel	38.17 ± 0.02	36.85 ± 1.46	32.14 ± 0.30	37.17 ± 2.65	38.86 ± 0.42	38.55 ± 0.96	37.17 ± 2.65	32.12 ± 1.65	29.51 ± 1.05	26.85 ± 2.74
b∗ peel	57.69 ± 0.05	58.82 ± 0.64	42.08 ± 2.08**A**	60.77 ± 0.69**B**	59.45 ± 0.08	60.09 ± 1.40	42.08 ± 2.08**A**	63.98 ± 0.05**B**	55.91 ± 1.30	58.25 ± 2.51
c∗ peel	69.20 ± 0.05	69.48 ± 1.32	53.00 ± 1.80**A**	71.32 ± 1.94**B**	71.05 ± 0.28	71.45 ± 0.71	53.00 ± 1.80**A**	71.63 ± 0.68**B**	62.58 ± 1.41	64.19 ± 2.99
h∗ peel	56.49 ± 0.01	57.89 ± 0.73	52.61 ± 1.07	58.54 ± 1.51	58.32 ± 2.35	57.29 ± 1.27	52.61 ± 1.07**A**	63.35 ± 1.22**B**	62.30 ± 0.47	65.24 ± 1.93
L pulp	54.04 ± 0.36	54.71 ± 1.81	44.61 ± 0.95**A**	41.42 ± 0.04**B**	42.31 ± 2.72	45.72 ± 2.56	44.61 ± 0.95**A**	52.02 ± 0.88**B**	57.33 ± 2.22	64.74 ± 1.41
a∗ pulp	8.60 ± 0.35	6.65 ± 0.66	9.65 ± 0.68	11.95 ± 1.61	9.47 ± 0.99	8.28 ± 0.23	6.68 ± 0.67	11.95 ± 1.61	9.89 ± 1.22	12.09 ± 0.23
b∗ pulp	27.75 ± 1.90	24.78 ± 1.28	14.66 ± 0.13	10.78 ± 1.62	13.40 ± 1.99	14.48 ± 4.88	25.40 ± 1.29**A**	10.78 ± 1.62**B**	46.54 ± 3.46	53.31 ± 1.50
c∗ pulp	29.13 ± 1.90	25.79 ± 1.34	17.71 ± 0.66	16.19 ± 2.20	16.54 ± 2.16	16.82 ± 4.38	26.27 ± 1.42**A**	16.19 ± 2.20**B**	47.78 ± 3.40	54.67 ± 1.50
h∗ pulp	72.61 ± 0.25	75.32 ± 1.06	56.27 ± 2.37**A**	41.52 ± 1.02**B**	53.76 ± 1.77	58.74 ± 8.55	75.25 ± 0.69**A**	41.52 ± 1.02**B**	77.23 ± 0.42	77.25 ± 0.30
pH	3.52 ± 0.05	3.57 ± 0.01	3.45 ± 0.15	3.78 ± 0.14	3.63 ± 0.01**A**	3.54 ± 0.01**B**	3.98 ± 0.01**A**	3.94 ± 0.01**B**	4.13 ± 0.01**A**	3.97 ± 0.01**B**
TA (% citric acid)	0.98 ± 0.03**A**	1.13 ± 0.02**B**	0.94 ± 0.03**A**	0.69 ± 0.02**B**	0.87 ± 0.01**A**	0.96 ± 0.01**B**	0.62 ± 0.01**A**	0.55 ± 0.02**B**	0.49 ± 0.01	0.52 ± 0.02
TSS (° Brix)	15.31 ± 0.12**A**	12.26 ± 0.08**B**	12.50 ± 0.57	12.82 ± 0.41	13.10 ± 0.01**A**	12.73 ± 0.01**B**	12.19 ± 0.01**A**	11.95 ± 0.02**B**	13.77 ± 0.02**A**	13.31 ± 0.01**B**
Vitamin C (mg/100 mL)	71.12 ± 5.21**A**	64.11 ± 1.87**B**	57.37 ± 2.03	59.84 ± 4.24	57.11 ± 0.16**A**	56.39 ± 0.08**A**	39.58 ± 0.73**A**	44.36 ± 0.49**B**	27.64 ± 0.43**A**	36.79 ± 0.10**B**
TPC (mg/L)	103.6 ± 0.2**A**	89.3 ± 1.3**B**	91.1 ± 0.1	106.6 ± 0.1	87.2 ± 0.7**A**	83.4 ± 0.7**B**	76.5 ± 0.7**A**	83.1 ± 0.7**B**	96.5 ± 0.1**A**	117.7 ± 0.4**B**
Total flavanones (mg/L)	434.40 ± 5.6**A**	269.57 ± 6.4**B**	134.99 ± 3.41	148.95 ± 5.31	205.00 ± 2.8**A**	167.60 ± 4.8**B**	188.00 ± 3.39	185.53 ± 3.58	334.97 ± 2.7**A**	432.46 ± 4.0**B**
Narirutin (mg/L)	206.68 ± 1.59	123.80 ± 1.70	41.78 ± 1.10	37.30 ± 1.84	43.50 ± 2.12	30.55 ± 2.19	39.30 ± 0.42	43.55 ± 0.78	45.13 ± 0.18	64.37 ± 0.52
Hesperidin (mg/L)	173.93 ± 2.83	120.68 ± 1.87	83.54 ± 1.36	100.43 ± 1.73	146.45 ± 0.64	126.45 ± 0.35	140.60 ± 2.83	132.65 ± 2.33	275.35 ± 1.91	347.90 ± 2.82
Dydimin (mg/L)	53.80 ± 1.27	25.10 ± 2.83	9.68 ± 3.41	11.23 ± 1.74	15.05 ± 0.07	10.60 ± 2.26	8.10 ± 0.14	9.34 ± 0.47	14.48 ± 0.67	20.19 ± 0.69
Anthocyanins (mg/L)	–	–	205.0 ± 1.4**A**	317.5 ± 3.5**B**	369.0 ± 2.8**A**	146.5 ± 2.1**B**	–	–	–	–
ORAC (μmol TE/g DW)	1,652 ± 247	1,916 ± 308	2,455 ± 210	2,587 ± 103	2,001 ± 94	2,112 ± 104	1,692 ± 59	1,871 ± 74	2,122 ± 33	2,026 ± 77

L* = lightness, h* = hue, a*, b*, and c* = color coordinates, TA, titratable acidity; TSS, total soluble solids; TPC, total phenolic content; ORAC, oxygen radical absorbance capacity. Results expressed as Mean ± standard deviation. Different letters mean statistical differences between samples ($p < 0.05$).

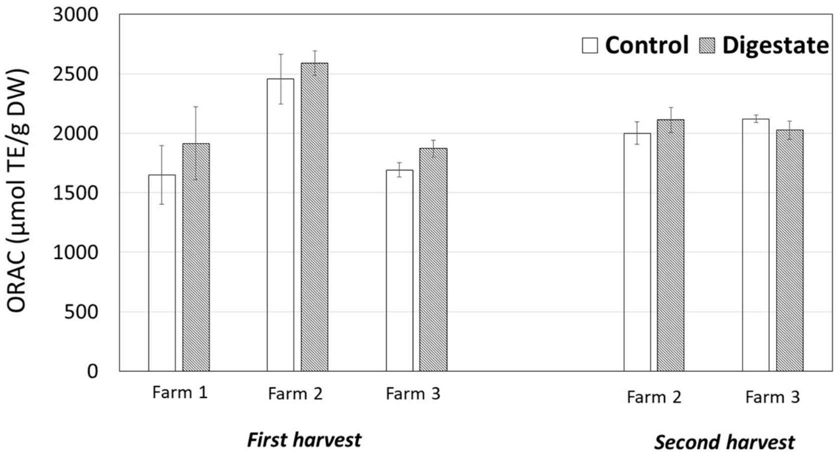


FIGURE 2
Antioxidant activity of flesh orange juice obtained from citrus harvested in the three different farms. The data are expressed as mean ± SD; $p \leq 0.05$.

The same can be said for CIELab indices for peel and pulp and antioxidant activity determined using ORAC assay (Figure 2).

With regards to Farm 2, since two harvests occurred, there is the need to consider them separately.

The first harvest resulted in fruits with most of the physicochemical parameters being comparable between the two treatments. In particular, the values of juice yield, pH, solid soluble showed no significant differences when fruits fertilized with digestate were compared to those treated with conventional chemicals.

Also, HPLC analysis for the determination of vitamin C content and flavanones concentration gave results not significantly different between the two studied groups.

On the other hand, a significant difference was observed for titratable acidity, that was higher in the flesh obtained from citrus treated conventionally (0.94 vs. 0.69%), and for the total phenolic content which, on the contrary, resulted positively affected when liquid digestate was used as fertilizer (106.6 vs. 91.1 mg/L).

In the measurements of fruits color, significant differences in the indices were observed between the two groups of samples. The peel of citrus fertilized with liquid digestate showed higher b*, and c* values, resulting in a brighter yellow color. When it comes to pulp, L* and h* indices resulted significantly different, with lower values for citrus treated with digestate. For the determination of antioxidant activity, ORAC assay was performed and the obtained results showed no significant differences between the two studied groups (Figure 2).

Since citrus fruits harvested in Farm 2 belong to the cv Tarocco Scirè (Blood Oranges), also the determination of anthocyanins was carried out as well. These values were significantly different between the two studied groups: it was found a higher concentration of anthocyanins was found in the juice obtained from oranges treated with liquid digestate (317 vs. 205 mg/L).

The second harvest occurred in Farm 2 showed similar flesh yields as well as comparable CIElab coordinates of peel and pulp, when the two groups investigated were compared.

Moreover, titratable acidity values for citrus grown with digestate fertilization were higher in comparison to conventionally fertilized citrus (0.96 vs. 0.87%). On the contrary, other physicochemical parameters, such as pH and total soluble solids, resulted in lower values for the juice obtained from fruits treated with microfiltered digestate.

Spectrophotometric determinations, i.e., total polyphenols content and anthocyanins concentration, showed higher values for fruits treated with conventional fertilizers. The same trend was followed by total flavanones concentration (205 vs. 167.6 mg/L). No significant differences were observed for antioxidant activity, determined by means of ORAC assay (Figure 2).

For the last farm involved in the study, Farm 3, two harvests were carried out.

The first one resulted in fruits and flesh with physicochemical parameters significantly different between the two groups investigated. In particular, the juice yield, the pH of the juice as well as total soluble solids were higher in the samples grown in the soil fertilized with chemicals. On the other hand, the content of vitamin C in fruits picked from trees treated with digestate was significantly different and higher compared to those harvested in the conventionally fertilized orchard (44.36 vs. 39.58 mg/100 mL). The concentration of total flavanones, calculated as the sum of the three most representative flavonoids, as well as the antioxidant activity, did not differ significantly, showing comparable figures (Figure 2).

Moreover, differences in the CIElab coordinates values, in particular peel parameters, such as b*, c*, and h* values, were observed, resulting in higher values for the digestate group. With regards to the pulp color coordinates, all of the parameters were significantly different when compared between the two soil treatments.

In the second harvest, significantly different results were obtained: the flesh yield was lower for fruits treated with digestate compared to the one obtained for citrus treated conventionally (35.92 vs. 47.43%). Lower values of pH and total soluble solids of the juice were obtained for oranges treated with liquid digestate.

Significant differences were noticed among the fruits in terms of secondary metabolites. Fruits collected from plants grown on soil amended with liquid digestate showed the highest amount of vitamin C (36.79 vs. 27.64 mg/100 mL) and total polyphenols (117.7 vs. 96.5 mg/L). The same trend was emerged for flavanones concentration (432.46 vs. 334.95 mg/L), among which hesperidin was found to be the most abundant flavanone in both groups.

Finally, significant differences in the pulp color were detected: L*, a*, b*, and c* values were higher in the fruits grown on trees treated with digestate compared to those irrigated conventionally. The values of the antioxidant capacity obtained using the ORAC assay showed no significant differences between the two groups (Figure 2).

5. Discussion

In this research work, two different fertilizers (conventional mineral fertilizer and digestate) and their effects on physicochemical parameters of citrus fruits, were compared with the aim to test further potential benefits of an innovative environmentally friendly fertilization strategy.

Table 3 reports the characteristic parameters for the quality of fruits collected in three different farms. Among these markers, titratable acidity, expressed as % citric acid and total soluble solids, reported as °Brix degrees are two of the most important ones. The acids content in juices tends to decrease along with the maturation of citrus fruit, mostly because of the use of these compounds as respiratory substrates, as well as, for the synthesis of new substances. Values of acidity recorded in the present study ranged from 0.49 (Farm 3) to 1.13% of citric acid (Farm 1). Another change that can be observed in the juice during fruits' development is sugar accumulation. In this regard, total soluble solids values were determined since they represent the main index of sugar content in the flesh. The values obtained for TSS ranged from 11.95 (Farm 3) to 15.31 (Farm 1). The trend for acid content and sugars in the current study is in agreement with the aforementioned statement (Liao et al., 2019), showing that the highest titratable acidity values are accompanied by the lowest sugars content values.

The pH values of the juices were within the normal range (3.52–4.13). As one would expect, the pH values are lower in the juices with more acidity.

Another index of citrus quality is the external citrus peel color, that is also generally used as a selection criterion throughout the supply and consumer chain (Selvaggi et al., 2023). In the current study, the color parameters obtained, quantitatively defined into three dimensions of hue, chroma, and lightness, showed variations between the two studied groups (digestate and conventional fertilization). Researchers (Byers and Perry, 1992; Saija et al., 1998; Pallottino, 2010) attribute the changes in rind color to the ripeness process, during which chlorophyll concentration decreases and carotenoid content increases.

In this study, the Vitamin C (ascorbic acid) values of oranges grown in different fertilization conditions were compared. Orange juices analyzed in this experimental study showed values of vitamin C comprised between 36.79 (Farm 3) to 64.11 mg/100 mL (Farm 1) when the flesh came from fruits (Del Amor et al., 2008) treated with digestate, whereas the ascorbic acid content was found to range from 27.64 to 71.12 mg/100 mL for the flesh obtained from citrus fruit treated with commercial fertilizers. The values found in this study confirm what was obtained by other authors (Martí et al., 2009; Marti et al., 2015; Rapisarda et al., 2010; Chanson-Rolle et al., 2016).

Moreover, being as the dominant group of flavonoids in citrus, flavanones concentration has been determined. In this experimental work, the concentration of three flavanones, namely narirutin, hesperidin, and didymin, has been quantified.

The results obtained for fruits collected during the first harvest in Farm 2 and during the second harvest in Farm 3 suggested that, the use of digestate, stimulated plant-resource reallocation from primary metabolism to secondary metabolite production, driving the synthesis of flavanones. In particular, citrus collected in Farm 2 during the first harvest showed an increase of flavanones' concentration by nearly 10%, while an increment by 29% was observed for fruits collected during the second harvest in Farm 3. These results were in agreement with previous studies reporting higher levels of secondary metabolites in organic carrots (Sharma et al., 2012), sweet peppers (Del Amor et al., 2008) and tomatoes (Panuccio et al., 2021).

In every tested juice, hesperidin represents the most abundant flavanone, with values comprised between 85.38 and 347.9 mg/L. While narirutin was the second most abundant flavanone in juices (values range from 30.56 to 206.60 mg/L), dydimin was the minor flavonoid identified in all studied juices (values ranged from 8.09 to 53.79 mg/L). The data obtained for the purpose of the present study are in agreement with those available in the scientific literature (Mondello et al., 2000; Gattuso et al., 2007; Selli, 2007), in which the orange juices tested presented a similar flavanones' profile.

Another class of flavonoids that has been investigated in the present research work is anthocyanins, the water-soluble pigments responsible for the cyanic color of fruits and vegetables. Since these pigments can be found only in blood oranges, their content was determined only for citrus collected in Farm 2 (cv Tarocco Scirè), whose values ranged from 146.5 to 369.0 mg/L, coherently with the results that can be found in literature (Rapisarda et al., 2000; Fabroni et al., 2016).

6. Conclusions

The present study highlighted the possibility of using the liquid fraction of digestate as a soil supplement to obtain multiple benefits to orange growth and quality. The most important fruit parameters of citrus quality, which depend also on nutrient supply, were evaluated and, for most of the physicochemical determinations, comparable results between the two groups were obtained with no negative effects on quality parameters when digestate was used as fertilizer.

On the contrary, in some cases (first harvest in Farm 2 and second harvest in Farm 3), the content of bioactive compounds investigated, i.e., vitamin C, total flavanones and total polyphenols, was positively affected by the use of digestate as soil amendment.

Considering the overall agronomic performances, digestate can be a useful option for replacing synthetic fertilizers, avoiding the negative effects associated with conventional mineral fertilizers. Since this environmentally friendly soil amendment holds huge potential, there is the intention to assess it in future experiments on other crops.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

Conceptualization: AC, RS, and PM. Data curation and methodology: AC. Formal analysis: DS and MH. Funding acquisition and supervision: GP. Investigation and writing—review and editing: RS and PM. Visualization: RS and GP. Writing—original draft: AC and RS. All authors have read and agreed to the published version of the manuscript.

Funding

This research was carried out in line with the project titled Sustainable and innovative soil improvers for Mediterranean crops—FERTIMED (CUP G54I20000560009). Moreover, it has been financially supported by the departmental project "Sostenibilità ed innovazioni della ricerca in agricoltura, alimentazione ed ambiente" (UPB 5A722192180).

Conflict of interest

AC was employed by Mediterranean Nutraceutical Extracts (Medinutrex) srls, Catania, Italy and PM was employed by Centro Ricerche Produzioni Animali (CRPA) SpA, Reggio Emilia, Italy.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Agouillal, F. M., Taher, Z., Moghrani, H., Nasrallah, N., and El Enshasy, H. (2017). A review of genetic taxonomy, biomolecules chemistry and bioactivities of citrus hystrix DC. *Biosci. Biotechnol. Res. Asia* 14, 285–305. doi: 10.13005/bbra/2446

Alburquerque, J. A., de la Fuente, C., Campoy, M., Carrasco, L., Nájera, I., Baixauli, C., et al. (2012). Agricultural use of digestate for horticultural crop production and improvement of soil properties. *Eur. J. Agron.* 43, 119–128. doi: 10.1016/j.eja.2012.06.001

Amenta, M., Ballistreri, G., Fabroni, S., Romeo, F. V., Spina, A., and Rapisarda, P. (2015). Qualitative and nutraceutical aspects of lemon fruits grown on the mountainsides of the Mount Etna: a first step for a protected designation of origin or protected geographical indication application of the brand name 'Limone Dell'Etna.' *Food Res. Int.* 74, 250–259. doi: 10.1016/j.foodres.2015.04.040

Bettini, O. (2018). *Citrus Annual 2018*. Rome: FAO.

Byers, T., and Perry, G. (1992). Dietary carotenes, vitamin C, and vitamin E as protective antioxidants in human cancers. *Annu. Rev. Nutr.* 12, 139–159. doi: 10.1146/annurev.nu.12.070192.001035

Chanson-Rolle, A., Braesco, V., Chupin, J., and Bouillot, L. (2016). Nutritional composition of orange juice: a comparative study between french commercial and home-made juices. *Food Nutr. Sci.* 07, 252–261. doi: 10.4236/fns.2016.74027

Davies, F. S., and Albrigo, L. G. (1994). *Citrus*. CAB International, Wallingford, 254.

Del Amor, F. M., Serrano-Martínez, A., Fortea, M. I., and Núñez-Delicado, E. (2008). Differential effect of organic cultivation on the levels of phenolics, peroxidase and capsidiol in sweet peppers. *J. Sci. Food Agric.* 88, 770–777. doi: 10.1002/jsfa.3140

Di Giacomo, A., Calvarano, M., Calvarano, I., Di Giacomo, G., and Belmusto, G. (1989). Il succo delle arance pigmentate Italiane. *Essenze. Deriv. Agrum* 59, 273–289.

Doyeni, M. O., Stulpinaite, U., Baksinskaite, A., Suproniene, S., and Tilvikiene, V. (2021). The effectiveness of digestate use for fertilization in an agricultural cropping system. *Plants* 10, 1734. doi: 10.3390/plants10081734

Fabroni, S., Ballistreri, G., Amenta, M., and Rapisarda, P. (2016). Anthocyanins in different citrus species: an UHPLC-PDA-ESI/MS *n*-assisted qualitative and quantitative investigation. *J. Sci. Food Agric.* 96, 4797–4808. doi: 10.1002/jsfa.7916

Food and Agriculture Organization (2017). *Market and Policy Analysis of Raw Materials, Horticulture and Tropical (RAMHOT) Products Team*. Rome: Food and Agriculture Organization of the United Nations.

Gattuso, G., Barreca, D., Gargiulli, C., Leuzzi, U., and Caristi, C. (2007). Flavonoid composition of citrus juices. *Molecules* 12, 1641–1673. doi: 10.3390/12081641

Giuseppe, M., Emanuele, C., Rita, P., Roberta, S., and Biagio, P. (2020). Performance evaluation of digestate spreading machines in vineyards and citrus orchards: preliminary trials. *Heliyon* 6, e04257. doi: 10.1016/j.heliyon.2020.e04257

Hans, S., and Eder, P. (2013). *End-of-Waste Criteria for Biodegradable Waste Subjected to Biological Treatment (Compost and Digestate): Technical Proposals*. Luxembourg: Publications Office of the European Union.

Jin, K., Pezzuolo, A., Gouda, S. G., Jia, S., Eraky, M., Ran, Y., et al. (2022). Valorization of bio-fertilizer from anaerobic digestate through ammonia stripping process: a practical and sustainable approach towards circular economy. *Environ. Technol. Innov.* 27, 102414. doi: 10.1016/j.eti.2022.102414

Kimball, D. (1991). *Citrus Processing*. Dordrecht: Springer Netherlands.

Lado, J., Gambetta, G., and Zacarias, L. (2018). Key determinants of citrus fruit quality: metabolites and main changes during maturation. *Sci. Hortic.* 233, 238–248. doi: 10.1016/j.scienta.2018.01.055

Li, S., Lo, C. Y., and Ho, C. T. (2006). Hydroxylated polymethoxyflavones and methylated flavonoids in sweet orange (*Citrus sinensis*). *Peel. J. Agric. Food Chem.* 54, 4176–4185. doi: 10.1021/jf060234n

Liao, L., Dong, T., Qiu, X., Rong, Y., Wang, Z., and Zhu, J. (2019). Nitrogen nutrition is a key modulator of the sugar and organic acid content in citrus fruit. *PLoS ONE* 14, 356. doi: 10.1371/journal.pone.0223356

Manetto, G., Cerruto, E., Papa, R., and Selvaggi, R. (2022). *First Results of Digestate Spreading Trials in Mediterranean Crops. AIIA2022: Biosystems Engineering Towards the Green Deal, September 19–22, 2022 Palermo—Italy*. New York, NY: LNCE, Springer Nature.

Mantovi, P., Moscatelli, G., Piccinini, S., Bozzetto, S., and Rossi, L. (2020). *Microfiltered Digestate to Fertigation: A Best Practice to Improve Water and Energy Efficiency in the Context of BiogasdonerightTM*. New York, NY: Springer, 497–499. doi: 10.1007/978-3-030-13068-8_124

Marti, J., Savin, R., and Slafer, G. A. (2015). Wheat yield as affected by length of exposure to waterlogging during stem elongation. *J. Agron. Crop Sci.* 201, 473–486. doi: 10.1111/jac.12118

Martí, N., Mena, P., Cánovas, J. A., Micol, V., and Saura, D. (2009). Vitamin C and the role of citrus juices as functional food. *Nat. Prod. Commun.* 4, 506. doi: 10.1177/1934578X0900400506

Möller, K. (2015). Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. *Agron. Sustain. Dev.* 35, 1021–1041. doi: 10.1007/s13593-015-0284-3

Mondello, L., Cotroneo, A., Errante, G., Dugo, G., and Dugo, P. (2000). Determination of anthocyanins in blood orange juices by HPLC analysis. *J. Pharm. Biomed. Anal.* 23, 191–195. doi: 10.1016/S0731-7085(00)00269-7

Morra, L., Cozzolino, E., Salluzzo, A., Modestia, F., Bilotto, M., Baiano, S., et al. (2021). Plant growth, yields and fruit quality of processing tomato (*Solanum lycopersicon* L.) as affected by the combination of biodegradable mulching and digestate. *Agronomy* 11, 100. doi: 10.3390/agronomy11010100

Murano, R., Maisano, N., Selvaggi, R., Pappalardo, G., and Pecorino, B. (2021). Critical issues and opportunities for producing biomethane in Italy. *Energies* 14, 2431. doi: 10.3390/en14092431

Muscolo, A., Settineri, G., Papalia, T., Attinà, E., Basile, C., and Panuccio, M. R. (2017). Anaerobic co-digestion of recalcitrant agricultural wastes: characterizing of biochemical parameters of digestate and its impacts on soil ecosystem. *Sci. Total Environ.* 586, 746–752. doi: 10.1016/j.scitotenv.2017.02.051

Nagy, S., Shaw, P. E., and Veldhuis, M. K. (1977). *Citrus Science and Technology*. Westport, Conn: Avi Pub. Co.

Nkoa, R. (2014). Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. *Agron. Sustain. Dev.* 34, 473–492. doi: 10.1007/s13593-013-0196-z

Orzi, V., Riva, C., Scaglia, B., D'Imporzano, G., Tambone, F., and Adani, F. (2018). Anaerobic digestion coupled with digestate injection reduced odour emissions from soil during manure distribution. *Sci. Total Environ.* 621, 168–176. doi: 10.1016/j.scitotenv.2017.11.249

Pallottino, F. (2010). *Assessment of Tarocco Orange Fruit Firmness by Standard and Non-Destructive Tests*. Ashburn: Università degli Studi della Tuscia.

Panuccio, M. R., Mallamaci, C., Attinà, E., and Muscolo, A. (2021). Using digestate as fertilizer for a sustainable tomato cultivation. *Sustainability* 13, 1574. doi: 10.3390/su13031574

Pappalardo, G., Selvaggi, R., Bracco, S., Chinnici, G., and Pecorino, B. (2018). Factors affecting purchasing process of digestate: evidence from an economic experiment on sicilian farmers' willingness to pay. *Agric. Food Econ.* 6, 16. doi: 10.1186/s40100-018-0111-7

Pappalardo, G., Selvaggi, R., and Pecorino, B. (2022). Biomethane production potential in southern Italy: an empirical approach. *Renew. Sustain. Energy Rev.* 158, 112190. doi: 10.1016/j.rser.2022.112190

Peng, W., Lü, F., Hao, L., Zhang, H., Shao, L., and He, P. (2020). Digestate management for high-solid anaerobic digestion of organic wastes: a review. *Bioresour. Technol.* 297, 122485. doi: 10.1016/j.biortech.2019.122485

Rapisarda, P., Camin, F., Fabroni, S., Perini, M., Torrisi, B., and Intrigliolo, F. (2010). Parameters, influence of different organic fertilizers on quality and the Δ15N, Δ13C, Δ2H, Δ34S, and Δ18O values of orange fruit (*Citrus sinensis* L. Osbeck). *J. Agric. Food Chem.* 58, 3502–3506. doi: 10.1021/jf903952v

Rapisarda, P., Fanella, F., and Maccarone, E. (2000). Reliability of analytical methods for determining anthocyanins in blood orange juices. *J. Agric. Food Chem.* 48, 2249–2252. doi: 10.1021/jf991157h

Rapisarda, P., and Intelisano, S. (1996). Sample preparation for vitamin C analysis of pigmented orange juices. *Ital. J. Food Sci.* 8, 251–256.

Saija, A., Tomaino, A., Lo Cascio, R., Rapisarda, P., and Dederen, J. C. (1998). *In vitro* antioxidant activity and *in vivo* photoprotective effect of a red orange extract. *Int. J. Cosmet. Sci.* 20, 331–342. doi: 10.1046/j.1467-2494.1998.177057.x

Selli, S. (2007). Volatile constituents of orange wine obtained from Moro oranges (*Citrus sinensis* [L.] Osbeck). *J. Food Qual.* 30, 330–341. doi: 10.1111/j.1745-4557.2007.00124.x

Selvaggi, R., Zarbà, C., Pappalardo, G., Pecorino, B., and Chinnici, G. (2023). Italian consumers' awareness, preferences and attitudes about Sicilian blood oranges (Arancia Rossa di Sicilia PGI). *J. Agric. Food Res.* 11:100486. doi: 10.1016/j.jafr.2022.100486

Sharma, K. D., Karki, S., and Thakur, N. S. (2012). a chemical composition, functional properties and processing of carrot—a review. *J. Food Sci. Technol.* 49, 22–32. doi: 10.1007/s13197-011-0310-7

Singleton, V. L., Orthofer, R., and Lamuela-Raventós, R. M. (1999). "[14] Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent," in *Methods in Enzymology* (New York, NY: Academic Press), 152–178.

Turner, T., and Burri, B. (2013). Potential nutritional benefits of current citrus consumption. *Agriculture* 3, 170–187. doi: 10.3390/agriculture3010170

Valenti, F., Porto, S. M. C., Selvaggi, R., and Pecorino, B. (2018). Evaluation of biomethane potential from by-products and agricultural residues co-digestion in Southern Italy. *J. Environ. Manage.* 223, 834–840. doi: 10.1016/j.jenvman.2018.06.098

Valenti, F., Porto, S. M. C., Selvaggi, R., and Pecorino, B. (2020). Co-digestion of by-products and agricultural residues: a bioeconomy perspective for a mediterranean feedstock mixture. *Sci. Total Environ.* 700, 134440. doi: 10.1016/j.scitotenv.2019.134440

Zeng, Q., Zhen, S., Liu, J., Ni, Z., Chen, J., Liu, Z., et al. (2022). Impact of solid digestate processing on carbon emission of an industrial-scale food waste co-digestion plant. *Bioresour. Technol.* 360, 127639. doi: 10.1016/j.biortech.2022.127639

frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 30 June 2023
DOI 10.3389/fsufs.2023.1174623

Check for updates

OPEN ACCESS

EDITED BY
Gary Wingenbach,
Texas A&M University, United States

REVIEWED BY
Roberta Sisto,
University of Foggia, Italy
Raffaella Pergamo,
Council for Agricultural and Economics Research (CREA), Italy

*CORRESPONDENCE
Luca Altamore
✉ luca.altamore@unipa.it

RECEIVED 26 February 2023
ACCEPTED 01 June 2023
PUBLISHED 30 June 2023

CITATION
Ingrassia M, Bacarella S, Bellia C, Columba P, Adamo MM, Altamore L and Chironi S (2023) Circular economy and agritourism: a sustainable behavioral model for tourists and farmers in the post-COVID era.
Front. Sustain. Food Syst. 7:1174623.
doi: 10.3389/fsufs.2023.1174623

Circular economy and agritourism: a sustainable behavioral model for tourists and farmers in the post-COVID era

Marzia Ingrassia[1], Simona Bacarella[1], Claudio Bellia[2], Pietro Columba[1], Marzia Maria Adamo[1], Luca Altamore[1]* and Stefania Chironi[1]

[1]Department of Agriculture, Food and Forestry Sciences, Università degli Studi di Palermo, Palermo, Italy,
[2]Department of Agriculture, Food and Environment, Università degli Studi di Catania, Catania, Italy

Introduction: In recent years, issues related to environmental and ecosystem protection have been given greater consideration than in the past. The goal of adopting sustainable development models is vigorously pursued in the European Union and is reflected concretely in the new Common Agricultural Policy 2023-2027. The circular economy can certainly be an emerging economic response that can effectively replace growth models centered on a linear view. Agriculture and tourism are two crucial sectors where the "green transition" should be encouraged to help achieve sustainability goals through economic circularity. Agritourism's activity may be relevant in contributing to a behavioral change based on ethical choices. The study aim is to find out if agritourism can be the forerunner for the green transition. The objective is to know motivations and current level of awareness and adoption of concrete behaviors of the circular economy by agritourisms and their guests. The tourists' preferences for Sicilian agritourism offerings were also observed.

Methods: Two types of surveys were conducted: a Census of the Sicilian Agritourisms active at an online travel agency and a sampling survey of the agritourism's visitors.

Results and discussion: The results showed that agritourism by its very nature carries the green transition, partly due to the enormous financial support of the new CAP. Second, it is a provider of quality food and ecosystem services, and a promoter of healthy behaviors and consumption of seasonal and local short-chain products by visitors, so it can be a vehicle for the adoption of the Mediterranean Diet as a sustainable lifestyle and food system. Tourists' propensity to seek out environmentally friendly products and green services can help to improve ethical, responsible, and sustainable tourism. A sustainable behavioral model for farmers and tourists was provided.

KEYWORDS

sustainable development, rural tourism, multifunctional agriculture, CAP, sampling survey, green transition, European funding, agri-food system

1. Introduction

In the new millennium, sustainable and efficient use of resources is the challenge that stimulates a better change in the way to produce, consume, and, ultimately, live. This challenge turns out to be increasingly important, especially for businesses operating in the agricultural sector (Whitfield et al., 2018). The answer to this challenge may be the attempt to meet the current demand for food, growing due to the increase in world population, using agricultural practices and techniques that allow for improving farm productivity and provision of environmental services without reducing resources, and at the same time regulating wastes and negative environmental externalities. The search for obtaining higher productivity "at any cost", typical of the post-industrial economy, through the increasing use of non-renewable resources, caused excessive use of inputs and rise of environmental costs. The intensification that has occurred in "conventional" agriculture often was accompanied by inefficient use of resources that damaged progressively the ecosystem. Although during the last 30 years, it was generally acclaimed that the production system based on value creation structures built on the linear model of extraction, production, consumption, and disposal are detrimental to the terrestrial ecosystems, only in the last 5 years, there has been a more concrete commitment by the European Union (EU) to the ambitious environmental and climate goals (Ghisellini and Ulgiati, 2020).

In addition, the COVID-19 pandemic in 2020 and the conflict between Russia and Ukraine in 2022 have further highlighted the fragility of our economic development model. Therefore, the EU has further accelerated its transition path (initiated in 2019 with the presentation of the European Green Deal) to a circular economy (CE) and sustainable development (SD), designing a resilience model based on energy independence, reduction of social and sanitary inequalities, and processes and behaviors more and more "digital" and "green" (Ingrassia et al., 2022a).

At the same time, the emphasis on issues related to protecting the environment and biodiversity has also increased considerably among people. The growing interest in "green" policies reflects a concerned society, more aware of the actual conditions of our planet. According to the literature, avoiding food waste and surplus become an issue also for consumers progressively moving toward diverse and healthier food patterns (Gómez and Martinez, 2023; Pedrotti et al., 2023).

In addition to the above, the COVID-19 pandemic has influenced individual behavior. The need to enjoy open spaces and stay in contact with nature has become of primary importance, particularly for urban citizens that felt a stronger need for vacations far from cities (Ingrassia et al., 2022a). Moreover, there was a decisive push to the very slowly initiated green transition. A rising desire to become more responsible for daily actions, also during traveling, was observed (Nocca et al., 2023). However, there is still a certain skepticism about recycled and reclaimed materials (Keränen et al., 2023).

In this framework, agriculture takes on a crucial role in green transition and sustainable efficiency. The circularity of the agri-food system is one of the prerequisites for achieving an optimal balance between economic and environmental sustainability. Circular economy (CE) in the agricultural sector regards the reduction of wastes generated in the production system, the recovery of food surpluses and waste, the use of by-products and food waste, the recycling of nutrients, and the production of biomaterials, but also changes in the food dietary and consumption regime were adopted (Renting et al., 2009; Ingrassia et al., 2022b).

The European model of agriculture was formulated in response to growing pressures from outside and within the European Union to reduce price support for agricultural commodities and introduced the philosophy that sufficient numbers of farmers ought to be kept on the land to sustain the characteristic landscape appearances and social structures of rural areas that are valued positively by wider society. Within this approach, at least at the theoretical level, agriculture is seen as one of several economic sectors in the countryside which, in combination with other activities—such as tourism and services—should guarantee the sustenance of viable livelihoods and quality of life in rural areas (Kachniewska, 2015). The concept of Multifunctional Agriculture (MA) was first introduced at the Earth Summit in Rio in 1992. Broadly speaking, MA refers to the fact that agricultural activity beyond its role of producing food and fiber may also have several other functions such as the management of renewable natural resources, landscape, conservation of biodiversity, and contribution to the socio-economic viability of rural areas. However, the meaning attributed to multifunctionality in international debates is ambiguous, as various institutions have adopted the term with slightly different interpretations and in relation to different policy agendas. Another tradition in the use of the concept can be traced back to the Food and Agriculture Organization (FAO) which more specifically refers to the situation in developing countries focused on the varied nature of agricultural activities and its multiple contributions to livelihood strategies of households and rural development. FAO uses the notion of multiple "roles of agriculture" (Bresciani et al., 2004), which in addition to environmental externalities also covers contributions of agriculture to development challenges such as food security, poverty alleviation, social welfare, and cultural heritage. A third important, and again different, contribution to the debate on MA is associated with the reform of the Common Agricultural Policy (CAP) of the European Union, which from the 1990s onwards adopted multifunctionality as an important cornerstone of its European Model of Agriculture. Indeed, the first official recognition of MA in the EU comes with the Agenda 2000, a package of reforms approved in 1999 inside the CAP that covered the period 2000–2006. From that date on, issues such as environmental protection and biodiversity began to take on an increasingly strategic role and weight in the CAP, so much so that they increasingly condition EU aid and funding toward the sector.

The EU farmers are nowadays facing new and more ambitious challenges in the market, innovation, and environmental-economic sustainability. The multifunctional farm, generally, carries out also activities of tourist reception and offering/selling of its products to the guests (direct sales), plus other educational activities (educational farming, agri kindergarten, and social agriculture), and can be defined in one term as agritourism activities. Moreover, a multifunctional farm also has other tasks, including maintenance of public green spaces, preserving the rural/agricultural local landscape and environment, using alternative energies, and overall contributing to the rural development of the territory, also increasing its tourism potential.

Certainly, strategies for the conservation and enhancement of the rural landscape have long been of growing importance, within the policies of individual EU countries (Pappalardo et al., 2018). In the past, the landscape was considered exclusively the place of primary production, but today, it is a multifunctional container able to promote the modernization of agricultural structures and the enhancement of territorial resources (environmental, tourist, social, etc.) in full respect of the environment (preserving biodiversity), climate, and the health of the inhabitants of rural areas as well as consumers of food products grown in them (Pappalardo et al., 2018). Agriculture, beyond the traditional role of food production, also assumes a service function for the community through the protection of the environment and natural resources, seeking integration of people with nature and the local territory (Sisto et al., 2022). Ultimately, thanks to the MA, the EU not only aims to support farmers' incomes by introducing the possibility of carrying out complementary activities to agriculture but also aims to ensure the maintenance of rural areas integrated with the peri-urban and urban territories through the enhancement of specific endogenous resources. Therefore, multifunctionality is not only in favor of the users and the environment but also a diversification of income sources for farmers which allows them to reduce income risks by relying on complementary activities. On this basis, the European Union focuses on multifunctionality, within the framework of Rural Development Programs, through specific measures to support farmers.

If multifunctionality is the heart of rural development, then agritourist activity is its flagship (Yang et al., 2010; Streifeneder and Dax, 2020). However, between these two concepts, a new way of understanding the farm moves, no longer and not only poured upon itself but open to urban and tourist flows, operationally and virtually connected to commercial channels, and able to intercept a new kind of demand that comes from the citizen.

According to the EU definition, the farmhouse is the estate offered by the farmer who uses his property as an accommodation for visitors/tourists to supplement his farm income. In Italy, farmhouses that offer farm-holidays services are known as "Agritourisms". The Italian laws (Edizioni Europee, 2023a,b) define "agritourist activities" as the reception and hospitality activities carried out by agricultural entrepreneurs using their farm, in a relationship of connection and complementarity with the activities of cultivation of the fund, forestry, and breeding of livestock, which must however remain main. It is therefore a structure whose main activities are those related to the agricultural world, followed by the processing of the land, the collection of its fruits, and the breeding of livestock, but which has been adapted to tourist reception. One of the purposes of agritourism is to recover a closer relationship with nature, with artisanal production methods, culture, and local people. For this reason, many agritourism structures offer various activities, such as participation in the different stages of products, such as wine, oil, cheese, cooking classes for those who like a Food-&-Wine holiday in Italy, or bike rental for paths on trails or the riding for a horse ride for those who want a sporting holiday. Choosing agritourism means approaching a rural world made of ancient traditions, handed down from generation to generation, and crafts that seemed destined to disappear, and enjoying a genuine and familiar welcome and the quiet of the countryside. Moreover, agritourism activity plays a social role as it acts as a link between urban and rural areas, and, in this sense, it can contribute to the adoption of more sustainable behaviors (Safonte et al., 2021).

In addition to agritourism, rural tourism is another concept that is included in the larger context of farm holidays. It has in common with agritourism the tourist's desire to stay in contact with nature and to keep well away from the busy life routine and the stress of the cities. It is possible to say that it went up as an inverse response to urbanization as this type of tourism offers the opportunity to spend time in a relaxing place, immersed in the sounds of nature doing something different like hiking, cycling, or just resting. Similar to the agritourism concept, rural tourism also misses a definition widely recognized. For example, in Finland, this type of tourism involves just the rent of cabins in a rural environment; and in Hungary and Slovenia, it assumes a connotation similar to the Italian agritourism; in fact, it regards accommodations in the rural environment, or just farmhouses, with activities related to the agriculture where tourists live in contact with farmer families. In the Netherlands, rural tourism concerns camping on farms that supply horse riding, cycling, walking, and so on (Darău et al., 2010). In addition, from the point of view of organizations and associations, attempts have been made to introduce a definition broadly accepted. The European Union defines "rural tourism" as "the activities of a person traveling and staying in rural areas other than those of their usual environment for less than one consecutive year for leisure, business and other purposes (excluding the exercise of an activity remunerated from within the places visited)" (European Environment Agency, 1998). The United World Tourism Organization (UNWTO) understands rural tourism as "a type of tourism activity in which the visitor's experience is related to a wide range of products generally linked to nature-based activities, agriculture, rural lifestyle/culture, angling and sightseeing". Rural tourism activities take place in non-urban (rural) areas that are characterized by the following traits: low population density; landscape and land-use dominated by agriculture and forestry; and traditional social structure and lifestyle. The Organization for Economic Co-operation and Development (OECD) tried to explain what rural tourism concerns (Woodward, 2004). In its report, the OECD describes all the variables that contribute to obtaining a definition that includes all the characteristics of rural tourism, that are: the link with places characterized by low population density and open spaces, small-scale enterprise, open space, contact with nature and the natural world, landscape and natural heritage, "traditional" societies, and "traditional" practices. The main features are the following: rural both in terms of buildings and settlements, and, therefore, usually small scale; traditional in character, growing slowly and organically, and connected with local families; and sustainable, in the sense that its economic development should help sustain the special rural character of an area, and in the sense that its development should be sustainable in its use of resources. Rural tourism embraces a wide range of activities and components such as accommodations, events, sports, treatments, and so on, acting together characterized by the country frame, far away from cities. In short, similar to agritourism, rural tourism should be seen as a potential tool for conservation and sustainability, rather than as an urbanizing and development tool of many different kinds, representing the complex pattern of rural environment, economy, and history. Nevertheless, rural tourism differs from agritourism because rural tourism activities are not necessarily carried out at a farm, ranch, or factory processing agricultural produce. Therefore, activities specific to rural tourism do not generate supplementary incomes for agricultural enterprises.

Mass tourism is among the forms of tourism that generate high negative impacts on the environment (Korstanje and George, 2020). Excess tourism occurs when the number of visitors increases dramatically, causing overpopulation in places where the local population is affected by temporary and seasonal tourism spikes (Nocca et al., 2023). This type of tourism also has long-term negative impacts on the local population in terms of general wellbeing (Nocca et al., 2023). The negative economic, social, and environmental impacts caused by mass tourism development necessitate the adoption of various sustainable tourism development strategies (Nocca et al., 2023). In this scenario, green tourism should be developed from the perspective of stakeholders; this community includes tour operators, travel agents, hotels, guests, and hosts (Bellia et al., 2021). Green tourism seeks to protect the environment and aims to achieve social, economic, and environmental sustainability. Most green and/or responsible tourism initiatives are based on the principle of balancing the economic, social, and environmental spheres (Aguiñaga et al., 2018). This new notion of tourism aimed at environmental protection and preservation requires a collective consensus and commitment from different stakeholders and the critical role of political leadership. Even in sustainable tourism, tourist satisfaction must be maintained at a high level so that a memorable experience can always be offered to travelers. However, it is imperative that tourists become more aware of the challenges of sustainability and themselves encourage the development by operators of sustainable and green tourism offerings starting from the very demand (from people/visitors/tourists). From large to small businesses, rural to urban areas, the concept of "green" can be used for all kinds of specialized tourism industries. Environmental responsibility has become a major concern for corporate image even in the tourism industry, and therefore for long-term business success (Markose et al., 2022).

The agritourism's activity and provision of multi-services to users/tourists may be relevant in contributing to a behavioral change through more environmentally sustainable choices, through more attention to ethical and ecological aspects, and by favoring the development of a more environmentally friendly economy. In this historical phase, ethical tourism offered by agritourisms appears, indeed, as an added value. Following this reasoning, the study aims to find out if agritourism can be the forerunner for the green transition and innovation in the tourist field. The question was: can "Agritourism" be a concrete response to achieving the green goals? The assumption is grounded in the principle that agritourism represents the linkage between the sense of place, the local identity, and economic-environmental sustainability (Selvaggi and Valenti, 2021). As is well known, many authors have written about the importance of agritourism activity for agricultural enterprises, recounting experiences and cases in different parts of Europe and the world. However, to the best of our knowledge, no one has ever delved into the issue related to whether and how far agritourism in the most backward rural areas can be the first example of tourism activities that are more likely to represent so-called green tourism. That is, to understand whether there are preconditions for a faster green transition and whether there is, at the same time, a demand from tourists for this kind of green supply. Therefore, to fill this gap in the current literature, the first objective of this study was to know the current level of transition to "circularity" practices by Sicilian agritourism(s), the agritourism entrepreneurs' awareness regarding the importance of applying these practices, the problems faced to implement sustainable and "circularity" practices, and to communicate this commitment to their tourists/visitors (make their clients aware of their commitment to the application of circular economy behaviors and practices). The second objective was to know the actual tourists/visitors' preferences and motivations for choosing agritourism to spend their holidays, investigating in deep the aspects related to sustainable behaviors and sustainable/green tourism. Particularly, the survey investigated visitors' preferences and opinions with respect to environmental sustainability and circularity practices and their propensity to adopt these practices in their daily life and also during travels/holidays.

1.1. Literature review

This literature review aims to assess the importance of agritourism in the literature on CE and to identify current research trends and possible gaps in the literature on CE and agritourism (Rodríguez et al., 2020; Melo Ribeiro and de Souza, 2022).

The circular economy (CE) is a new emerging economic response capable of replacing growth models centered on a linear vision, aiming for a reduction of waste and radical rethinking of the idea of products and their use over time. Specifically, the CE is based on the principles of prevention (changing the life stages of products), reuse (extending the useful life of products), material recovery (recycling and composting), energy recovery (waste-to-energy and anaerobic digestion), and product disposal (controlled landfill) to contribute to the reduction of pollution and regeneration of natural systems. The circular economy represents an economic model designed to be self-regenerating. All materials of biological origin are suitable for reintroduction into nature, while those with a technical component must be designed to provide the highest possible value before disposal. Therefore, this approach offers tools to improve and optimize sustainability even within the western Agri-Food System. However, the literature on the circular economy focuses more on the manufacturing sector, and only a few studies have been found on the tourism sector, in general, and on agritourism at national and international levels, despite being a sector where enormous energy and water consumption, food waste, and CO_2 emissions occur.

The European Commission, with its "Closing the loop—An EU action plan for the Circular Economy" of December 2015, puts together a set of guidelines to support the EU's move toward the CE. The Commission's latest report, 2019, presents the main achievements under the Circular Economy Action Plan and outlines future challenges to shape sustainable growth in the EU. Member states are working on this transition in different ways and at different speeds (EU, 2015).

> The European Parliament underlined that "the principles of circular economy should be the core element of [...] the national Recovery and Resilience Plans of Member States."

Many definitions of CE exist. The first time these principles were described was in 1966 thanks to professor Boulding Kenneth E. who tried to explain the idea of a closed system, referring to the limitation of natural resources (Boulding, 1966a,b); practically developed since 1990 by Pearce David and Turner R. Kerry, and recognized by policy-makers, academic researchers, and business consultants as fundamental to promoting sustainability in the modern economy. The term "Circular Economy" appears for the first time in 1990 as a link between the environment and economic activities. According to several studies, it is a wide concept that embraces more related fields such as the Green Economy, Bioeconomy, Sustainability, Waste, Industrial Ecology, Recycling/Reuse, and, broadly speaking, Environment (Merli et al., 2018).

It is possible to say that the circular economy is an umbrella concept that connects to a wide spectrum of notions and proposals.

Consequently, it becomes clear that there is no commonly accepted definition of circular economy, but it has many boundaries that explain it.

Kirchherr et al. (2017) point out that over the years, more than 114 definitions have been developed on this issue. Identifying the CE's relevance, the most important definitions seem highlighted below (Table 1).

Some attempts to describe this kind of economy are from governments, but also from academia and non-governmental organizations such as the Ellen MacArthur Foundation (EMAF).

In Table 2, some areas where the structure of CE, in its most diverse meanings, is discussed are shown.

In summary, the activities of agricultural multifunctionality are distinguished from similar activities carried out by other economic entities, by the connection with the activity properly agricultural, which must, with respect to them, remain principal. The multifunctional agricultural activity must therefore be organized by the farmer; take place mainly in pre-existing buildings and open spaces in the availability of the farm, suitably adapted for the purpose; involve activities/services/issues related to the system of places (farm, environment surrounding), products (agricultural), and culture (agricultural, ethnographic, naturalistic, food) in which it is taking place; and require, within the enterprise/farm, a contained organizational commitment, and however, such that it does not compress (and possibly develop) the main objective constituted by primary production resulting from the cultivation of land, animal husbandry, and forestry.

On the other hand, the constraint of the principality of agriculture is also a guarantee that the related activities do not assume such dimensions as to upset established balances of economic competition between similar activities carried out by operators in other productive sectors, subject to different regulatory (especially tax) treatments.

Moreover, they can produce the same quantity of goods consumed by the farmhouse itself, avoiding the waste of food and excessive production. Farms can also inform their clients about environmental friendliness to attract all those people who look for a sustainable experience. Actually, "hospitality and tourism are known for overuse and abuse of local resources, as 75% of all environmental impacts from resorts and tourism operations are a result of excessive consumption and emission of pollutants" (Curtis and Slocum, 2016).

Looking at the sphere of action of consumers, agritourism can contribute to improving their food styles and dietary behaviors. For example, people can choose to buy 0 Km products, can get information from the food labels, buy fewer and better products, and so on. Some of the criteria for a sustainable food system are the preservation of nutrients throughout the food chain, strengthening local food systems, promotion of access to dietary diversity, preservation of traditional agriculture practices, and promotion of local varieties (Sustainability of the food chain from field to plate: the case of the Mediterranean Diet). The adoption of more sustainable behaviors, such as the Mediterranean Diet, could be a possible answer to tackle this topic. Particularly, the Mediterranean Diet alias "Mediterranean lifestyle" is configured perfectly as a sustainable cultural system and it was recognized in 2010 as an intangible heritage of humanity by UNESCO, with representative headquarters in Sicily, the center of the Mediterranean. It brings together various environmental, social, economic, and cultural aspects, characterizing a series of factors such as production, nutrition, biodiversity, seasonality, tradition, conviviality, and enhancement of the territory (Iannetta and Padovani, 2015). Agritourism can play a perfect role in this scenario, and at the same time is an expression of food safety and psycho-physical well-being, attempting to outline the profile of this "new" green client/tourist/consumer.

1.2. Law review

The agritourism activity in Italy was regulated for the first time by Law 730/1985 and subsequently amended by Law 96/2006 which gave the regions the competencies of both the agricultural and tourism aspects. Law 730/85 imposed a link and complementarity with the purely agricultural activity so that access to any funds for the start of the agritourism activity or the improvements of the same structures was addressed exclusively to entrepreneurs agricultural. With Law 96/2006, the legislator wanted to provide clear guarantees about the definition of who is a farm owner and who is not for a greater guarantee of entrepreneurs and consumers. The law makes explicit the differences between the farm and the structures that although located in rural environments are not complementary to any agricultural activity.

The law n. 96/2006 has expressly defined the farm holidays as reception and hospitality activities carried out by farmers reiterating the characteristics of connection with agricultural activities such as the cultivation of the land, forestry and animal husbandry, and eliminating the complementarity character. The law also simplified what were administrative procedures and tax obligations for farmers to facilitate the undertaking of agritourism. The same law also allows the administration within the agritourism facilities as well as the production of the farm's traditional local products giving an additional connotation of food and wine quality to the agritourism offer (Bellia and Pilato, 2014). The legislation offers the possibility to widely diversify the offer giving the possibility to the entrepreneur to conceive and propose activities

TABLE 1 Selection of circular economy definitions in the literature.

Authors	Definitions
Andersen (2007)	"a system in which waste and other raw natural resources are taken and transformed into products rather than being disposed of, with a model designed to bridge the gap between the production cycle and the cycle of natural ecosystems"
Geng and Doberstein (2008)	"realization of [a] closed loop material flow in the whole economic system"
Yuan et al. (2006)	"the core [of the Circular Economy] is the circular (closed) flow of materials and the use of raw materials and energy through multiple phases"
Charonis (2012)	"economic system that is designed to be restorative and generative".
Macarthur Foundation (2013)	"an industrial system that is regenerative by intention and design. It replaces the concept of end-of-life with restoration, moves toward the use of renewable energy, eliminates the use of toxic chemicals, which undermine reuse, and aims to eliminate waste through superior design of materials, products, systems and, within this, business models"
European Commission (2015)	"... maintains the value of products, materials and resources in the economy for as long as possible, and waste generation is thus minimized"
European Parliament (2015)	"The circular economy is a production and consumption model that involves sharing, lending, reusing, repairing, reconditioning and recycling existing materials and products for as long as possible. This extends the life cycle of products, helping to minimize waste. Once the product has completed its function, the materials from which it is made are reintroduced into the economic cycle wherever possible. Thus, they can be continuously reused within the production cycle, generating further value"
Pollard et al. (2016)	"a circular economy is one that is restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times"
Bocken et al. (2016)	"design and business model strategies [that are] slowing, closing, and narrowing resource loops"
Geissdoerfer et al. (2017)	"regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling"

Source: Own Elaboration.

that are not necessarily realized entirely inside the company and in collaboration with public subjects. The agritourism activity thus becomes a tool to support a multifunctional agricultural model through the promotion of tourism forms considered sustainable for the countryside. The concept of multifunctionality, however, requires that further activities, in addition to the main one, must be organized by the farmer and take place mainly in existing buildings and open spaces available on the farm; concern activities and services in any case relate to the farm and its surrounding environment and require a limited organizational commitment. In the case of agritourism, moreover, regional regulations, in compliance with the provisions of national law, place size limits, albeit different between region and region, relative to beds (between 10 and 60) and the number of seats (between 10 and 80). These limits are not found in the reference legislation in many European countries and especially outside Europe where this activity is often regulated by the legislation of commercial activities. The opening up to the multifunctionality of agriculture, provided for by the European Union's Community Agricultural Policy, has represented, for many member countries, the possibility of diversification into other profitable activities or "alternative farms" (Phelan and Sharpley, 2011) as a strategy to promote a more diversified and sustainable rural economy as a response to the decline in agricultural incomes. Diversification strategies have served to stabilize and integrate agricultural incomes for producers in times of economic difficulty. The farm, as a form of entrepreneurial diversification in the company, was therefore promoted to address this agricultural context (Kim et al., 2019) without limiting the projects to the agricultural entrepreneur and therefore to the agritourism sector. In Australia, where the sector is the responsibility of the Department of Resources, Energy and Tourism, various structures have been built on farms that recover spaces according to their original uses, offering tourists experiences of rural life (Ecker et al., 2010). These structures are equipped with many restaurants which absorb almost all agricultural production, very often organic. Despite the reference development model of these structures is that of the tourist village, for the entrepreneur, the agricultural activity remains a priority.

Since the eighties in Italy, the farm has begun to spread in different regions, mainly supported by the rural development policies promoted by the European Union, which have considered it a tool to revitalize the territories and to support small-scale/medium-sized farms. However, Italian legislation regulated the agritourism activity differently from other other EU countries. In fact, it is a specific activity differentiated from other forms of rural tourism (Santucci, 2013). The national law (93/2006) and the various regional laws oblige the farm owner, and possibly the other members of the family, to devote themselves mainly to agricultural practices that must remain main and prevalent and allocate a part of their products to consumption within the structure. For these reasons, agritourism companies have over time developed more sustainable production techniques with a positive impact on biodiversity, the landscape, and natural resources. Farm holidays were an opportunity to reduce the negative externalities of agriculture on the environment but with performances lower than those guaranteed traditional forms of

TABLE 2 Examples of areas of interest in the circular economy definition.

Authors and year	Title	Source	Area of interest
Pearce and Turner (1990)	Economics of Natural Resources and the Environment	Baltimore: The Johns Hopkins University Press	Academics
United Nations (1993)	Integrated Environmental and Economic Accounting: Interim Version.	Handbook of National Accounting (interim version)	Policy-makers
European Commission (2015)	Closing the loop: An EU action plan for the Circular Economy	https://www.eea.europa.eu/policy-documents/com-2015-0614-final	Policy-makers
United Nations (2003)	European Commission, International Monetary Fund, Organization for Economic Co-operation and Development, and World Bank	Handbook of National Accounting: Integrated Environmental and Economic Accounting.	Policy-makers
McKinsey (2022)	No Time to Waste: What Plastics Recycling could Offer	https://www.mckinsey.com/industries/chemicals/our-insights/no-time-to-waste-what-plastics-recycling-could-offer	Consulting practitioners
MacArthur Foundation Google (2019)	Artificial Intelligence and the Circular Economy: AI as a Tool to Accelerate the Transition.	https://www.mckinsey.com/business-functions/sustainability/our-insights/artificial-intelligence-and-the-circular-economy-ai-as-a-tool-to-accelerate-the-transition	Consulting practitioners
George et al. (2015)	A Circular Economy Model of Economic Growth	Environmental Modeling and Software73: 60–63.	Academics
Scheepens et al. (2016)	Two life cycle assessment (LCA) based methods to analyze and design complex (regional) circular economy systems. Case: Making water tourism more sustainable	Journal of Cleaner Production, 114, pp. 257-268	Academics
Murray et al. (2017)	The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context	Journal of Business Ethics, 140(3),	Academics
Geissdoerfer et al. (2018)	Business models and supply chains for the circular economy	Journal of Cleaner Production, 190, pp. 712-72	Academics

Source: Own Elaboration.

tourism based on hotel accommodation and therefore far from the typical tourist market and its operators. This legislation has effectively excluded the agritourism sector from the tourism development policies that have affected both the national and regional territories.

The health crisis from COVID-19, which hit Europe and the entire globe in 2020, has upset the political programming of the European Union, forcing governance on the one hand to a postponement to 2023 of the new Common Agricultural Policy (CAP) and on the other to a redefinition of aid to businesses affected by the economic crisis, caused by the pandemic. For this reason, in addition to the sums already taken in the multiannual financial framework, the Commission has allocated an additional budget for the period 22/27, which has been merged into the "Next Generation EU" Fund, the main component of which is the Recovery and Resilience Fund (RRF) and accompanied by additional smaller funds for the financing of other intervention programs. The National Recovery and Resilience Plan (NRRP, PNRR in Italy) launched by the European Union is therefore an additional financial instrument immediately made available and equipped with 723.8 billion euros for grants and loans, to finance a package of measures. Among the additional complementary programs is the accredited Rural Development program of 8.1 billion. These sums have been made available to EU Member States, which have further implemented them with other own funds.

With this programming, the European Union has set itself as a long-term objective, even beyond the programming period 21/27, smart growth within the Community in line with the "European Green Deal" and the European intervention strategy "From Farm to Fork". This strategic objective is based on increased business competitiveness to be achieved through innovation and technological development, environmental sustainability through respect for the environment and mitigation of the effects of climate change, and inclusiveness as an ability to foster employment, equal opportunities, and social cohesion.

The launch of the new CAP 2023/2027 has forced member countries to draw up a single National Strategic Plan (NSP, PSN in Italy) within which each country has defined the areas of intervention through which to finance their main productive sectors. Within the national strategic plan, Italy through the measure SRD03 "Investments of farms for diversification in non-agricultural activities" promotes subsidy and support plans also for agritourism activities. Additional funding to support the agritourism sector is provided, also within the NSP, for olive-oil companies and for companies producing buffalo mozzarella DOP bell that intend to diversify their activities. In this case, it is support coupled with the income that will be paid directly to the farmer. With the NRRP, the Italian Government has made available to businesses a total of 222.1 billion euros, including co-financing, to finance programs for the digital transition (26.0% of the total funds), the ecological transition (37.0%), and the "Mezzogiorno" (the Italian geographical area comprising Southern and island Italy) (37.0%). The Plan is based on a series of "Missions" and sub-components that finance a wide number and types of structure and infrastructure investments, also integrated with each other, for the country's recovery and resilience through public calls and notices intended for state or local governments, businesses, and citizens.

Two concrete examples in connection with this study are precisely the Measure M2C1 "Circular economy and sustainable agriculture" and the Measure M1C3 "Culture and tourism" which provide funds for investments in favor of "sustainable/green" tourism. The NRRP and the other accompanying measures, therefore, allow access to funding also to farmhouses by equating them to other classic tourist facilities. This is the first time Italian farmers have additional funds to those allocated by rural development policies (as it was until the last programming), available for investments in agritourist activities. However, for the Italian agritourisms, the access to NRRP funds is limited by the agritourism Italian Law's directions that imposes the ifferee of farming as a main activity as opposed to tourist reception, pointing out the primacy of agricultural activity to the tourist one, and thus sizing agritourism enterprises to micro or small dimensions. The economic convenience of agritourist investments is therefore limited to the start-up of agritourist activities or to others strictly related to farming activity. For a single farm, investments to expand the offer of services or equipment may not be convenient in considering that the Low 96/2006 puts tight limits on the increase of the number of rooms, beds, and table settings. Therefore, Law 96/2006 appears a restriction for the development of this sector toward the multifunctionality of agriculture and green transition, crucial points of the EU's green agenda, embedded with relevance in the CAP.

1.3. A brief history of Sicilian agriculture

In the middle of the Mediterranean, Sicily is the largest island in terms of both the size of the territory and the population. Historically, this position has led it to play a strategic economic and political role in the interaction of peoples (Europeans, Africans, and Asians) around the Mediterranean basin. This role was maintained until, with the discovery of America, the economic and political interests of European countries moved to the Atlantic causing a consequent regression of most of the countries of the Mediterranean basin. The populations that have circulated on the Sicilian territory and that have influenced its evolution have been numerous (Benedetto and Giordano, 2008). The first human traces in Sicily date back to the Neolithic period when the populations of the Near East introduced agriculture and breeding but throughout prehistoric times the island was at the center of large flows of cultural evolution that from the eastern Mediterranean spread to the Iberian Peninsula involving different populations of the Mediterranean basin. Over time other populations have influenced Sicilian society, introducing knowledge and an increasingly complex agricultural, cultural, urban, and artistic heritage (Badami, 2021). The Phoenicians brought wheat and vines to the island, and the Greeks influenced the process of urban, political, demographic, cultural, and economic evolution; the Romans, introducing the latifundia and making Sicily the granary of Rome, made the economy of the island complementary to that of Italy but have also ensured a long period of peace. After the Romans, the Byzantines arrived on the island for a short time, and then the Arabs with whom lemon, bitter orange, and the Zibibbo vine were introduced from the Far East as well as great innovations in techniques and irrigation works. Arab domination was followed by that of the Normans who introduced on the island the model of the organization of the feudal societies of Northern Europe while ensuring the peaceful coexistence between populations of different origins and cultures thus producing positive effects on the evolution of architecture, of culture, science, and economics (Renda, 2003; Bacarella, 2021). Later, in Sicily, came the Angevins and began the economic and social decline of the island that continued with the Aragonese, the Spanish, and the Savoy government until we arrived today (Hamel, 2011). The presence over time of the numerous immigrant or conquering populations as well as European dominations has left evident traces on the territory, in society, in the production of Sicily of cultural influences that translate into an artistic heritage, urban planning, architecture, customs, and traditions extremely rich and varied present in most of the cities and towns of the island. This same complexity is still found today in typical food production and an extremely varied gastronomic culture (Chironi et al., 2021). Sicilian agriculture is also the result of the different influences received by the numerous dominations present on the island territory as well as the consequence of the numerous pedoclimatic peculiarities that characterize the territory. There is, therefore, a very differentiated agriculture because of the various territorial characteristics and the great biodiversity of the island in terms of plant varieties and animal breeds that determine a typical production difficult to find in other regions or countries. In Sicily, agricultural activity changes its organization to meet the needs of modern consumers and the market in relation to the opportunities provided by regional, national, and community agricultural policy regarding health aspects, the enhancement of the typicality, the multifunctionality of agriculture, and the protection and enhancement of the territory (Bacarella, 2021). On the island, there are three macro-categories of agriculture, industrialized agriculture, quality and typical agriculture, and sustainable agriculture, which are spaces in different environments and different areas of the Sicilian territory. In this context, the cultural and natural heritage of Sicily also finds a great economic contribution from activities related to agriculture and tourism. On the one hand, the farmer with his/her activity creates agricultural and forestry systems consistent with the environmental potential and, on the other hand, contributes to the realization of agri-food productions connected with the territorial cultural traditions (Bellia et al., 2022). The agritourism activities and typical products facilitate the permanence of the farmer in rural areas and contribute in this way to the recovery and enhancement of the rural environment through the recovery and enhancement of rural construction, the promotion of craft, agro-industrial, catering, and gastronomy activities in the regional, national, and foreign contexts.

2. Materials and methods

2.1. Study design

For this study, two types of surveys were conducted: a Census (AN1) of the Sicilian Agritourisms active in the online travel agency "Booking.com" and a sampling survey (AN2) of the agritourism's tourists/visitors in the period from July 2020 to September 2022. The collected data were classified, summarized, shown, and inferred using descriptive statistics techniques. For AN1, the farm owners (FO)/managers (FM) were interviewed. A set of quali-quantitative variables was observed to highlight the main traits that characterize their practices. AN2 observed socio-psychographic and experience characteristics of tourists, food consumption behavior, travel intentions, activities preferred, and other characteristics that may help to design a tourist's profile and make a segmentation based on common features (clusters of tourists). Moreover, an attempt to link the holidays/travel/accommodation preferences and the tourist's profile (considering socio-psycho-demographic, travel experience, lifestyles, purchase intentions, etc.) was made.

2.2. Census and sampling survey design

AN1: For the Census of Sicilian Agritourisms, the reference statistical universe was the totality of Sicilian farms that also carried out tourist accommodation activities (agritourisms) in the selected period. This statistical population was obtained from official sources (official list of the Sicily Region of companies) that have received authorization to carry out agritourism activities (Regional Law 25/94 art. 4 and 5, updated on 31/12/2020) that was $N = 771$. Subsequently, only the agritourisms operating in the online travel agency Booking.com were chosen for three reasons: because their presence on booking.com allowed agritourisms to be easily found by tourists wanting to plan a vacation, because it is an indicator of a certain level of attention to communication through the web, and because booking.com also allows for ratings from guests after staying at the accommodations. The selection allowed us to obtain a list of $N = 337$ agritourisms. Therefore, a selection of those with customer satisfaction rates from 3 to 5 stars was made and a list of N = 138 agritourisms was obtained. These farmhouses were contacted by telephone by the research team to ask for their willingness to participate in the survey and $N = 109$ agritourism businesses gave their consent.

AN2: The reference population for the identification of the sample size of tourists/visitors was considered undefined or infinite statistical population. Therefore, under the assumption of an undefined population number, a sample of tourists/visitors, $n = 630$, interviewed was considered appropriate for this investigation (with the hypothesis of $p = 0.955$ and $q = 0.5$ and the calculated sampling error of 4%). After having balanced the sample on the basis of some socio-demographic variables (e.g., gender, age, and educational level), and after having eliminated incorrect questionnaires, it was possible to use $n = 531$ questionnaires, in this case, with the hypothesis of $p = 0.955$ and $q = 0.5$, the calculated sampling error is between 4% and 5%, and appears very acceptable for this type of study.

2.3. Types of interviews and questionnaires

For this survey, qualitative and quantitative variables (quali-quantitative variables) were analyzed. The variables were chosen by authors based on a review of the relevant literature (Nocca et al., 2023) on circular tourism and previous studies of territorial slow and green tourism (Bellia et al., 2021, 2022; Ingrassia et al., 2022a).

For AN1, the agritourisms owners (farm owners alias FO) were interviewed face-to-face in the period July 2020–September 2020. In some cases, the farm managers (FM), e.g., marketing directors, hospitality/communication managers, etc., were interviewed as an alternative to or in addition to the entrepreneur.

The interviews were carried out using a specifically structured questionnaire for the face-to-face interviews at wineries or eventually sent by email if producers asked to fill it in at a different time (Google Drive was used to create the online questionnaire format). The questions were aimed to find out about the type of reception, visiting and hospitality, level of services offered, tourist channels used, etc.

For AN2, the interviews with tourists who had stayed at the identified agritourisms in the period from July 2020 to September 2022 were carried out in the following way. Specialized surveyors carried out the interviews on-site during the visitors' stay at the agritourisms in the period July 2020–September 2020. During this period, the interviewers of the research team visited the selected farmhouses on scheduled days, generally at the end of the stay of tourists at the farmhouse, explained the purpose of the survey, and asked tourists if they were willing to participate in this study. In the case of a positive response, tourists were first asked to sign a written consent and then they were asked to fill out the questionnaire in spaces equipped with tables and benches outdoors. All participants were followed during the filling in of the questionnaire by the surveyor. Moreover, interviews with a second sample of tourists who had stayed at the selected agritourisms in the period September 2020–September 2022 were carried out using a digital form of the same questionnaire that was sent to tourists by e-mail or instant messaging applications after having received their written consent to participate in the survey.

A properly structured questionnaire was prepared for interviews with tourists. This questionnaire was used both for face-to-face interviews and those using emails and social networks. The questionnaire was also prepared in the English language.

The questionnaire initially included questions aimed at finding out the personal, socio-economic, and origin information of the tourists interviewed. Then, it contained open and closed questions aimed at outlining opinions on the visit and stay at the farmhouse and motivations for choosing this type of holiday.

TABLE 3 Agritourisms' characteristics.

Variables		%
Role of the respondent	Owner	49
	Office worker	29
	Family workers	22
Agritourism's years of activity	From 1 to 2 years	16
	From 3 to 5 years	29
	From 6 to 8 years	33
	From 9 years and more	22
Economic subsidies received to support agritourist activity	No	36
	Yes. Funds for agricultural holdings	62
	Yes. Funds for rural tourism	4
	I do not know	2
Agritourism be reached by public transport	Yes	13
	No	87
Presence of a shuttle bus	Yes	29
	No	71

TABLE 4 Application of circular economy at the agritourisms.

Variables		%
Apply circular economy practices	Yes	80
	No	20
Difficulty to apply the Circular Economy model	Yes	16
	No	84
Use of financial incentives to facilitate the adoption of the Circular Economy model	Yes	16
	No	84
Need for greater incentives and a more decisive policy orientation to implement the Circular Economy	Yes	96
	No	4
Desire to adopt or increase environmental management and/or economic circularity measures in the future	Yes	64
	No	0
	Maybe	36

TABLE 5 Use of environmental certifications at the agritourisms.

Variables		%
Environmental certification	Yes	69
	No	31
Think to adopt environmental certification	Yes	43
	No	5
	I do not know	52
	ISO 14001	23
	EMAS	10
	Ecolabel	50
Which certificate	Organic	10
	Demeter	4
	Environmental associations	3
Adopt eco-sustainable practices	Yes	98
	No	2
Guest information about the environmental compatibility	Yes	75
	No	25

3. Results

3.1. Results of agritourisms analysis

Official Statistics provided by the Italian Institute of Statistics (Istituto Nazionale di Statistica, ISTAT) highlight that, in 2021, there were 25,390 farms in Italy (ISTAT, 2023a). The largest growth was in the Islands (+8.2%) and the South (+1.5%). The multifunctional farms (which offer at least three services) are 38% of the total (+21.3% compared to 2011) and once again the Islands (Sicily and Sardinia) have the highest increase of MF farms (+51.5% compared to 2011). The farms run by women are 8,762 (34.5% of the total), an increase of 1.3% compared to 2020. As it was described in Paragraph 1.2., the establishment of the accommodation service in the activity of agritourism was stated by the Italian framework Law n. 96/2006, which states (article 2, paragraph 3.a), "*providing accommodation in lodgings or open spaces intended for the stay of campers*", followed by subsequent regional laws. The provision of accommodation for overnight guests by farms is the most popular agritourism service in Italy: more than 94% of agritourism farms today offer this service (ISTAT, 2023b).

Following the directions of the regional Law, Sicilian agritourism's accommodations were made in pre-existing rural farm buildings. Respondents confirmed that new buildings and new structures are not eligible for funding for carrying out agritourism activities. According to the law, the renovation of buildings must preserve the architectural and landscape features of the building and if possible preserve the interior features of the buildings (e.g., fixtures and floors), especially in cases where they have typicality related to the use of materials or construction methods typical of the place. According to respondents, most of the accommodations are in original structures, renovated to preserve their original architectural forms, with thick stone walls, exposed wooden beams, roofs, and terracotta floors. Regional rules (laws, regulations, and circulars) establish the

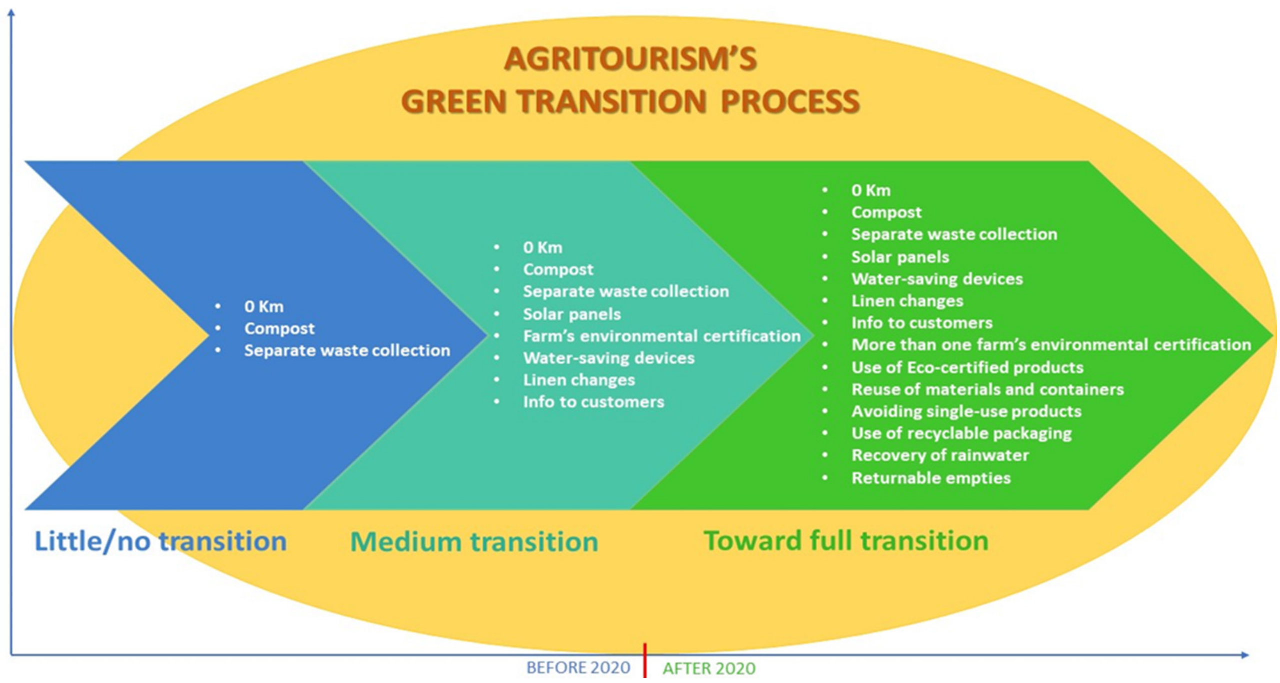


FIGURE 1
Agritourism's green transition process and determining factors.

maximum number of beds that each company can make and the minimum requirements of the premises, furnishings, and services (in particular, hygienic) to ensure adequate comfort for guests. Respondents said they offered guests rooms, with attached bathrooms, as is generally the case in hotels; independent apartments equipped with independent toilet facilities, kitchen, and dining room; and in some cases, entire independent apartments equipped with independent services. Often they offer breakfast or half or full board treatments that bring seasonal products, of their production or local farms. Moreover, respondents said that in the agritourism farm, they organize recreational and cultural activities that are not properly connected with agricultural activity or land development, like a swimming pool or tennis court which were, however, included in the accommodation rate.

From the interviews with entrepreneurs/agritourism managers, the following findings were highlighted.

The higher percentage of respondents are the owners (49%), followed by the office workers (29%) and family workers (22%) (Table 2). The majority of agritourisms, within the Sicilian sample, live for 6 years or more, however, the presence of new farmhouses reveals a positive aspect despite the challenges due to the COVID-19 pandemic. Particularly, 33% declared to carry out this activity from 6 to 8 years, 29% from 3 to 5 years, 22% for more than 9 years, and 16% from 1 to 2 years (Table 3). Moreover, 62% of respondents declared to have received funds for supporting agritourism activities, contrarily 36% said never got one (Table 2). Unfortunately, the majority of respondents declared they do not have a private vector (71%) to connect the agritourism with the main arrival terminals and it is a weakness for the business itself. Moreover, 87% of the FO/FM declared that the firm is not reachable by public means of conveyance (Table 3).

Concerning the main agricultural activities of farms (see Supplementary Figure 1), most of the respondents (67%) declared to produce "fruit and horticultural products", followed by "only horticultural products" (36%). In addition, beekeeping (29%) and livestock farming (22%) were practiced. The production and consumption of local and/or 0-Km foods help to reduce the carbon footprint and negative externalities.

It was asked to FO and FM how important was for them to include a list of certain activities in the agritourism's offer. It was asked to respondents to classify a list of further activities they will be willing to add to their current offer, in ascending order, from the most important to the less. Results (see Supplementary Figure 2) show that the most important services for agritourisms are natural excursions or/and walk in the woods; swimming pool; mountain biking; SPA and wellness; traditional cooking classes; and educational workshops and food preparation (bread, preserves, jam, and tomato sauce). All of them match the type of activities that tourists would like to try during a farm holiday.

Interestingly, 89% of respondents said that their guests ask for additional activities to be carried out during their stay at the agritourism but not necessarily at the agritourism farm. Therefore, this question was made for tourists (see Paragraph 3.2).

TABLE 6 Sample characteristics.

Variables	Values/attributes	Percentage
Gender	Female	53%
	Male	47%
Age	18–29	18%
	30–39	24%
	40–49	20%
	50–59	21%
	>60	17%
Country of Origin	Italy	56%
	Other countries	44%
Education	High school or less	20%
	Bachelor's degree	30%
	Master's degree	34%
	Postgraduate	16%
Occupation	Professional/executive	13%
	Employee	33%
	Entrepreneur	14%
	Student (full time)	9%
	Working student	3%
	Retired	15%
	Unemployed	8%
	Other	5%
Annual household net income	<25,000 €	10%
	25,000 €–50,000 €	57%
	More than 50,000 €	33%
Type of tourist	Families with children	47%
	Couples	41%
	Group of friends	12%
Length of stay	One day trip	22%
	From 1 to 3 days	55%
	From 3 to 7 days	20%
	More than 1 week	3%
Once you reach your destination, which means of transport do you prefer to use to reach the accommodation?	Private means of transport	29
	Car/motorbike rental	56
	Other (e.g., public bus, car with driver, etc.)	15

3.1.1. Focus on agritourism's green transition and sustainable behavior choices

In addition, a focus on the agritourisms degree of environmental sustainability and familiarity with behaviors and practices of CE.

Most of the Sicilian agritourisms declared to apply circular practices (80%), with no difficulties (84%), and a small part of them said they have experienced difficulties during the implementation process (16%), such as logistic problems, high starting costs, complex bureaucratic aspects, and unclear information from public administration offices. Indeed, 64% of the interviewees are willing to adopt or increase sustainable and circular practices (Table 4).

The 84% of agritourisms has benefited from funds aimed to facilitate the implementation of circular economic practices, such as tax reductions (e.g., waste collection taxes), incentives for phytoremediation, and to make feasible business plans (Table 5). The economic support received is sourced mostly from the rural development program in Sicily (47%, data not shown). Despite these aids, Table 3 almost the totality of the sample agrees with the need for more funds (96%) to accelerate the green transition and fast implementation of circular behaviors at the firm level (64%).

Moreover, it was asked if they had environmental certifications (Table 5) or adopted sustainable practices (see Supplementary Figure 3). Regarding the agritourism's commitments implemented toward the environment, most of the participants (69%) declared to have environmental certification, like the Ecolabel (50%), ISO 14001 (23%), EMAS (10%), etc., which guarantee products with good standards and reduced environmental impact (31% said that do not have still, data not shown). In addition, 43% of entrepreneurs declared to be intended to obtain any environmental certificate in future.

As a confirmation of that, most parts of the FO/FM interviewed (98%) declared to have implemented eco-sustainable practices.

The most used sustainable practiced are (Supplementary Figure 3) separate waste collection (97%), compost (87%), solar panels (53%), saving water devices (51%), and change of linen in accordance with customers' needs (51%).

Moreover, they usually inform their guests about the environmental compatibility of their farm and the sustainable behaviors adopted in the farm (75% of respondents), and only 25% of the FO/FM declared to be deficient in communicating (directly or indirectly through the services and activities offered) to its guests the value of the high compatibility of the farm with the application of sustainable practices and circular economy.

Finally, it is possible to summarize agritourism's green transition process generalizing from the Sicilian case, with the help of a visual representation (Figure 1).

Figure 1 shows the synthesis of results from the agritourism population. Particularly, it highlights the initiated process of transition before 2020 and the development that this process will have in future, showing the factors that outcome from results in this study. It is interesting to note that this process will be as fast as possible for farmers to invest in the digital and green transition. Results highlighted a good level of awareness and will to change from the offer side and the only limit seems to be the lack of investments made so far due to the scarce entity of public subsidies.

3.2. Results of tourist analysis

The second part of the analysis focused on tourists who have been guests of the agritourisms in the selected period. Results show

TABLE 7 Tourists' reasons for traveling.

Variables	Never	Rarely	Occasionally	Frequently	Very often
Leisure	5.5	7.5	24.4	32.3	30.3
Work	44.3	22.4	13.9	13.4	6.0
Visiting family and friends	10.0	23.4	33.3	25.4	8.0
Spend time with the family	14.4	17.4	25.4	23.9	18.9
Health/thermal treatments	54.2	31.8	10.9	2.0	1.0
Religious purposes	66.2	24.4	8.0	1.0	0.5

TABLE 8 Tourists' preferred type of holidays.

Variables		%
Preferred tourist destination	Nature	69
	Capitals or cities of art	78
	Beach	71
	Mountain	41
	Lake	16
	Food and wine	30
	Sporting events	7
	Sporting activities	7
	Religion/pilgrimage	15
	Therma	18
	Culture and entertainment	34
Preferred tourist facility	Sailing cruise	6
	BandB	46
	Vacation rental	3
	Hostel	3
	Tourist resort	3
	Agritourism	11
	Hotel 2–3 stars	13
	Hotel 4–5 stars	11
	Caravan	4

TABLE 9 Tourists' travel preferences.

Variables		%
Have you ever been to an agritourism?	Yes	89
	No	11
Do you think the COVID-19 pandemic has significantly changed your travel preferences?	A lot	30
	Quite a lot	36
	Little	24
	At all	10
Types of agritourism preferred	Standard agritourism	15
	Superior agritourism	62
	Luxury agritourism	23

that the sample was quite balanced with regard to gender (53% female and 47% male participants), range of age, country of origin, and education (Table 6).

The highest percentage (35, 3%) are people between 20 and 29 years; followed by the age group 30–39 years (23, 4%) and over 60 years (15%) which are nearly matched by 14, 4% of respondents between 50 and 59 years of age. According to data about the highest educational level, a master's degree and graduation from high school show a more substantial result, both around 30%, followed by a bachelor's degree with 21%.

Families with children were the main lovers of agritourisms (47%) followed by couples (41%) and groups of friends (12%). Apparently, in the period of investigation, 56% of tourists were Italians and 44% were from foreign countries, mainly from Europe; this is probably due to the restrictions to travel during 2020 and part of 2021 because of the COVID-19 pandemic. Previous official statistics showed a slightly higher number of foreign tourists that chose Sicily for agritourism.

According to guests, Sicilian agritourism appears like an ideal accommodation for couples, families, and groups of travelers from Italy and other foreign countries that like to have a holiday "in the green". Results showed that tourists like to stay more frequently at the agritourism from 1 to 3 nights (55%) but also a longer stay (from 3 to 7 days) or a "one-day" trip is pleasing (20–22%). Only 3% of tourists declared to stay more than 1 week. These tourists are those who often like to stay to go around the surrounding area with cars and visit cities of art and ancient villages, and/or sites of historical-archaeological or naturalistic significance, agritourism being the base for sleeping and dining. Generally, families and groups prefer to spend 1 week or more; couples prefer to stay from 1 to 3 nights.

One of the main issues highlighted by guests is the lack of public transportation or shuttle buses to connect farmhouses to the nearest towns or villages. This deficiency was also noted in interviews with owners of agritourism facilities. However, most of the respondents declared that they used private means of transport (29%) and rental care/motorbike (56%) to reach the nearest places (Table 6).

Moreover, the impact of the COVID-19 pandemic on tourists' personal travel choices and changes in travel preferences was investigated. Results showed an interest in slow tourism

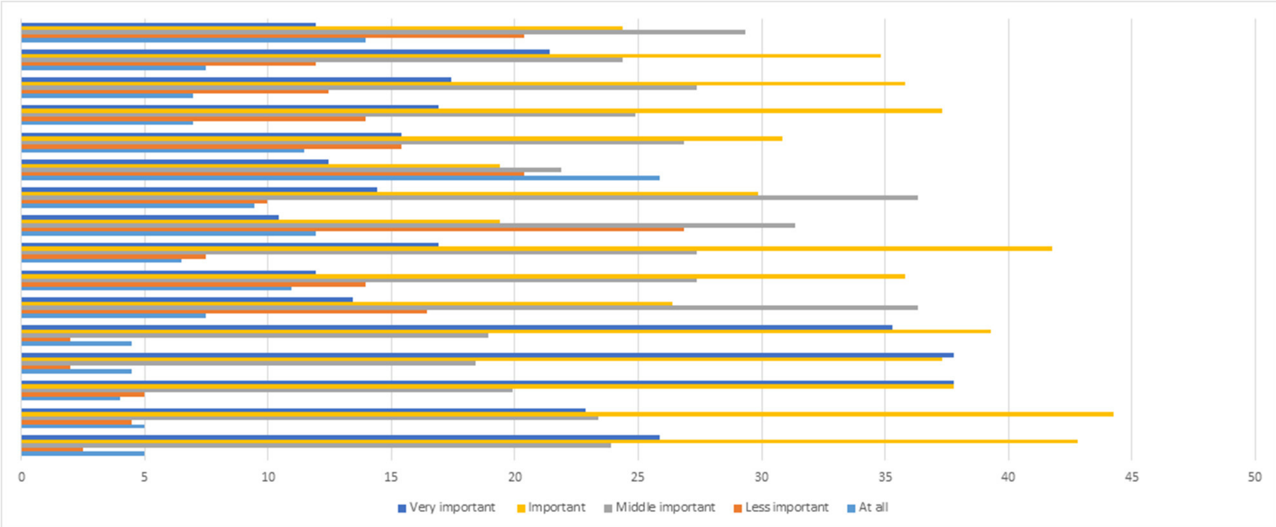


FIGURE 2
Reasons to prefer agritourism to another type of accommodation.

(83%). Data not shown. Further corroboration of the substantial inclination for places surrounded by nature came from the fact that most people after the lockdowns preferred slow tourism and a holiday in the countryside in contact with nature.

The first question asked to tourists was aimed to know how often they were used to travel and their general travel habits (Supplementary Figure 4). Almost all of them answered to travel several times a year (see Supplementary Figure 4). The highest percentage is among people who travel once or twice a year (48%), or at least three times (34%), while a lower percentage is registered for those who rarely take a trip (5%).

The main reasons for traveling were, mainly, leisure and spending time with family (Table 7). Also, visiting friends and relatives is a push factor for a journey.

With regard to the preferred tourist destination (Table 8), the most voted option chosen was "Capitals and cities of art" with 78% of preferences followed by beaches (71%), nature (69%), and mountains (41%). Moreover, culture & entertainment (34%) and food & wine (30%) were also appreciated.

Table 8 shows the results of the question about the type of facility tourists usually prefer for their holidays. It is possible to see that the majority of respondents like to stay at Bed and Breakfast (46%) or hotels (24%). And 11% of respondents said to prefer agritourism.

With regard to the change of travel destinations or holiday preferences after the COVID-19 pandemic, it is possible to observe from results that, generally speaking, tourists think that the pandemic influenced "a lot" and "quite a lot" their own travel preferences (Table 9). Therefore, future choices will involve vacations away from crowded tourist destinations (57%), outdoor places in contact with nature (57%), and trips during the low season (35%). The 20% of respondents will not change anything more than before. Moreover, 89% of respondents declared to have been at an agritourisms in their lives (Table 9). By the way, even if few participants opt for agritourism, they declared to like superior (62%) or luxury (23%) accommodations and facilities. This suggests that most people look for comfort and sophistication with a wide spectrum of amenities and services (Table 9).

The main reasons to prefer agritourism to another type of accommodation (Figure 2) are traditional cuisine and local food (both with 75% of "important" and "very important"), healthy food (71% of "important" and "very important), healthy environment (44% important and 23% very important), contact with nature (43% important and 26% very important), excursions (42% important and 17% very important), experience local places and culture (21% very important, 35% important, and 24% middle important), and accommodation without crowding problems (31% important and 27% middle important). The naturalistic aspect and the genuineness of agritourism are the driving characteristics that guide customers toward that choice.

Regarding the preferred type of activity to carry out at agritourism (Figure 3), walks in the woods and nature reserves cover the highest rate (74%), followed by natural excursions (70%) and tasting of local and seasonal products (70%). However, there is a considerable demand for "SPA" and wellness centers (49%) that can be reconnected with the high request for prestigious agritourisms as outlined above.

According to the results, 89% of guests ask for additional activities to carry out during their stay at the agritourism (Figure 4), not necessarily offered by the agritourist firm itself but available in the surrounding area. Particularly, visiting cities and villages (44%); making excursions (31%) to know sites of naturalistic interest; making trekking (18%) and mountain biking; participating in local festivals (9%); and visiting wineries (4%).

3.2.1. Focus on tourists' sustainable behavior and choices

The second part of the interviews regarded the tourists' knowledge of the circular economy and their propensity to adopt sustainable practices.

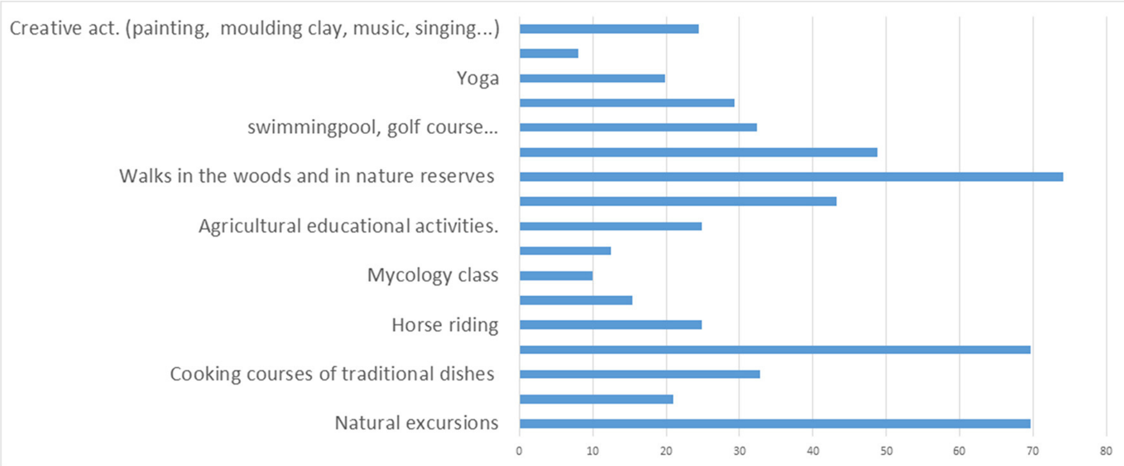


FIGURE 3
Preferred type of activity to carry out at an agritourism.

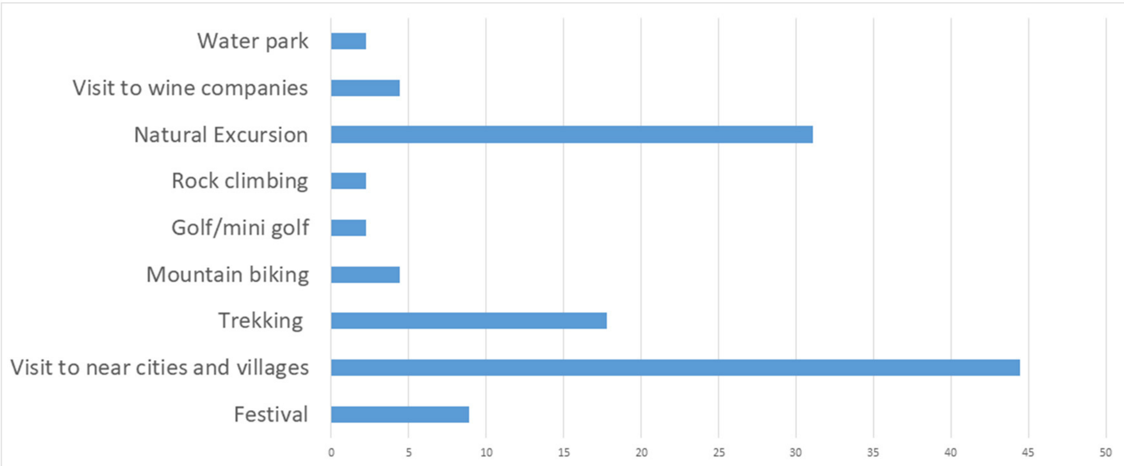


FIGURE 4
Additional activities asked to enjoy the territory.

The first question asked to tourists was about their self-described conviction to call themselves an environmentalist. Results show (Table 10) that a high percentage of respondents declared themselves to be an "environmentalist" (49%), even if there is a consistent portion that has doubts (51%).

The question (Table 10) "According to your experience at Sicilian agritourisms, are you satisfied of sustainable practices or circular economy measures applied?" shows a high rate of applicants who are not sure about the effective implementation of sustainable actions (72%). Motivations in support of the answer "no" (4%) may be related to the lack of any evidence or information about the implementation of measures related to the circular economy.

Indeed, to the question "Do you think it's easy to find and/or book a place that meets the requirements of circular economy and sustainability?", 47% of the respondents state that they do not know, maybe because there is still an unclear and inefficient promotion by agritourism. Approximately 33% of tourists answer "yes". Instead, motivations (open answers) given in support of the answer "no" (20%) are little information and publicity; low supply; low attention to the topic from clients and entrepreneurs; lack of investments; circular economy is still not a widespread culture; there are not online travel agencies that put together this offer; and, in most cases, unless you're voluntarily taking a green holiday, it's hard to find solutions that fully respect the environment; circular economy measures are expensive for both the client and the entrepreneur.

However, tourists declare to be willing to pay a higher price to buy a more sustainable product/service (50%), and 42% said it would be possible (maybe) (Table 10).

The level of knowledge and information of tourists with regard to the meaning of the concept of "circular economy" was studied. To simplify the question, along with the "yes" or "no" answer, some definitions were asked (Figure 5). Results show that the

TABLE 10 Sustainable behavior of respondents.

Variables		%
Would you call yourself "environmentalist"?	Yes	49
	No	20
	I do not know	31
How did you hear about circular economy's principles?	Social networks	26
	Internet	58
	Television	26
	School	5
	University	20
	Work	12
	Word of mouth	3
	Personal interest	1
	I don't know	1
Would you be willing to pay a higher price to buy a more sustainable product/service?	Yes	50
	No	8
	Maybe	42
According to your experience at Sicilian Agritourisms, are you satisfied of sustainable practices or circular economy measures applied?	Yes	24
	No	4
	Maybe	72
Do you think it is easy to find and/or book a place that meets the requirements of circular economy and sustainability?	Yes	33
	No	20
	I do not know	47

majority of respondents are aware of the basic meaning of circular economy. An important finding is the percentage of "no" (66%) to the definition "it is a closed loop recycling process" and the percentage of "yes" (37%) to the definition "it is based on the model take-make-waste".

It means that even if the general meaning of circular economy is widely recognized, there is still a significant portion of people who do not have a clear idea about the difference between the actual economic linear model and the circular one. Most importantly, a great lack of clarity is evident about the principle of closed-loop which means keeping products and materials in use and regenerating rather than degrading natural systems.

It should be good to inform citizens better through tv and institutional communication about what CE means and its applicability in daily life. The highest percentages registered to the question "How did you hear about circular economy's principles?" (Table 10) are for the internet (58%), television, and social networks (26% both).

With regard to the respondents' level of worry about environmental issues and climate change, according to respondents (Table 11), a high percentage declare they are worried about environmental issues and most of them (almost 74%) are willing to change their habits and prefer to consume local food to preserve and value the short production chain.

The linkage between sustainability and economic, social, cultural, and environmental concepts is accepted by 78% of respondents. It means that there is a widely recognized need for multifunctional coordination. Anyway, the largest part of the interviewed (82%) reports more effective political and social changes to make possible actions in support of the environment.

However, the largest number of tourists (63%) showed interest in the question "How important is it for you, in your everyday life, to adopt sustainable practices to tackle environmental problems" (Figure 6).

Some differences were observed when investigating things considered important for tourists when traveling (Figure 7). Specifically, the antithetical evidence is the high rate for green services (44%), information about the eco-friendliness of the establishment (73%) and eco-certificates (35%), to produce the minimum possible pollution (48%), and to spend time surrounded by nature (48%) and zero-emission activities (46%). On the other hand, there is a high request for the daily change of towels (29%) and the agreement with the statement "comfort and quality-price ratio are more important than green practices" (31%).

Finally, thanks to the results, it was possible to summarize the profile of tourists who choose a farm holiday at an agritourism with details about their behaviors with regard to sustainable practices and their holiday preferences and motivations. Figure 8 provides a synthesis of the correlated segments of tourists, highlighting a demand—increasingly more and more aware—for green and sustainable tourism. This demand can be satisfied by agritourisms if they will be faster than other multi-service providers in this process of transition.

4. Discussion

Nowadays principles of the circular economy and the green transition are becoming more and more important on a global scale. Results from both surveys demonstrate a great willingness to change. Most people are aware of future modifications for our planet due to environmental issues. Over the years, many different factors have emerged, thus the common thread is the need for change.

Focusing the attention on Italy and specifically to the Sicilian agritourisms, results highlight the desire of both farmers and guests to improve the actual level of transition toward the increasingly assiduous use of circular economy practices and good environmental behaviors. According to this, people are willing to pay more for sustainable products and services, thus it can encourage more agritourisms to adopt a green/eco-labeled production, also for those respondents who answered to be not sure to introduce environmental certifications in future.

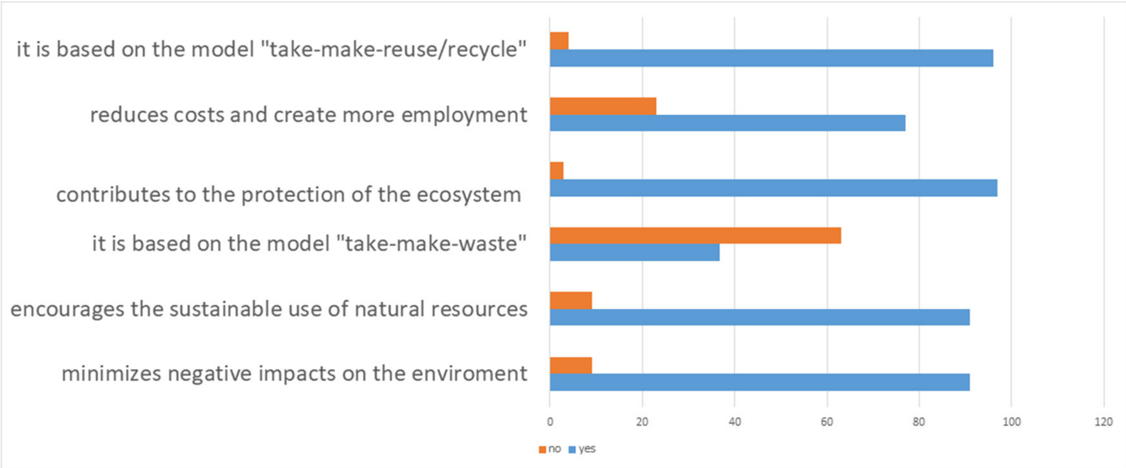


FIGURE 5
Definition of circular economy according to tourists.

TABLE 11 Tourists' level of agreement with statements regarding the environmental issue.

Statements regarding the environmental issue	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
I'm really worried about environmental issues	7	5	6	28	53
Sustainable tourism preserves the environment and the natural beauty of the world	8	8	4	34	45
I prefer to consume local and non-industrial food	8	6	13	32	40
I'm willing to change my habits to help the environment	7	7	8	43	33
More effective political and social changes are needed to protect the environment	9	5	3	17	65
Sustainability is linked to economic, social, cultural, and environmental concepts	9	5	7	31	48
The acceleration of climate change is also caused by the harmful effects of greenhouse gases	10	5	7	32	45
Climate change and pollution may have contributed to the spread of the COVID-19	14	20	28	25	12

Even if there is still a significant portion of respondents who do not have an academic or correct knowledge of what circular economy is, its main function is recognized and shared; namely, a system in which each product or component is designed to be reused in a loop guaranteeing a transition toward sustainable development.

It is widely recognized that this sustainable development path must originate from the linkage between sustainability and economic, social, cultural, and environmental actions to avoid an asymmetric transition. Already in 2010, the European Commission devised a strategy to be achieved by 2020. The purpose was more jobs and better lives thanks to smart, sustainable, and inclusive growth. These three priorities put forward by Commission meant (European Commission, 2010):

- Smart growth: developing an economy based on knowledge and innovation;
- Sustainable growth: promoting a more resource-efficient, greener, and more competitive economy;
- Inclusive growth: fostering a high-employment economy delivering social and territorial cohesion.

In the tourism industry, agritourisms can be the forerunner for this transition. It represents the linkage between the sense

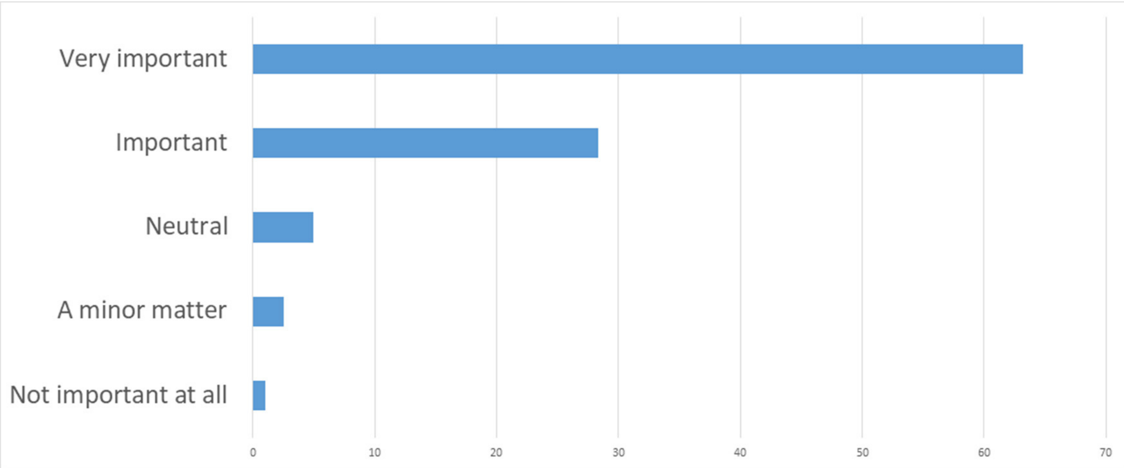


FIGURE 6
Tourists' interest in sustainable practices adopted to tackle environmental problems.

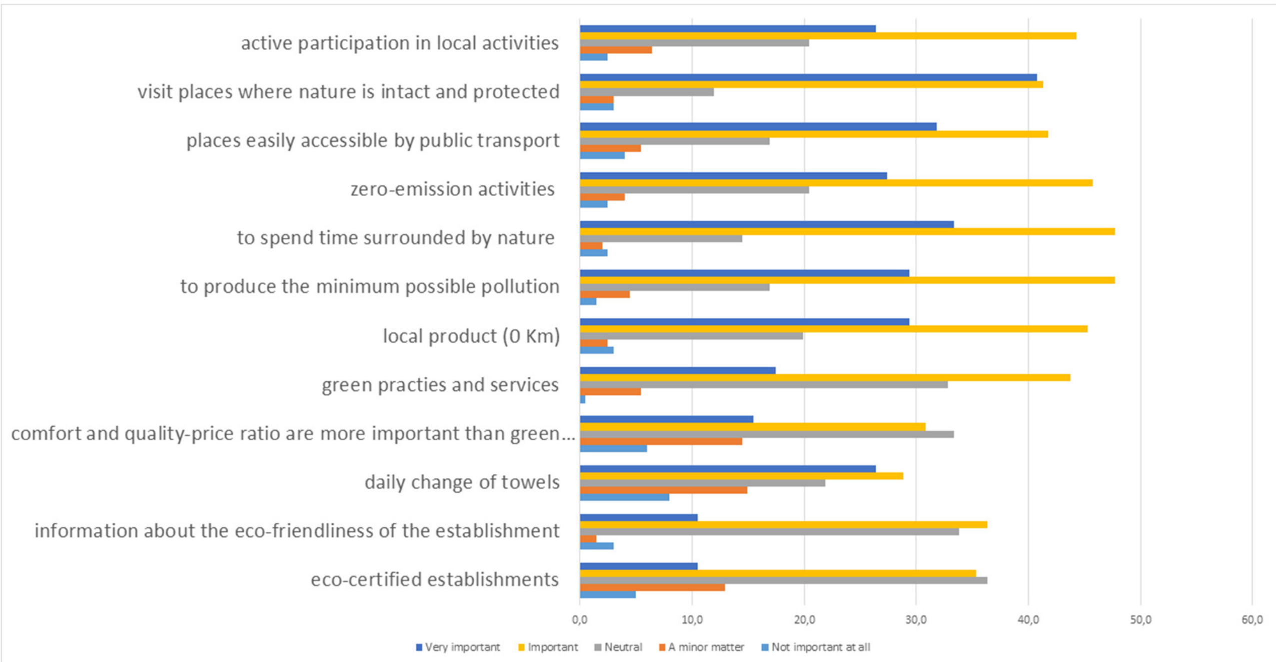


FIGURE 7
Important characteristics for tourists when traveling.

of place, the local identity, and the economic-environmental sustainability and it helps to valorize local communities offering typical products from the short chain. Farmhouses can help to achieve goal n.12 of the Sustainable Development Goals included in the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States. Among the 17 goals, the 12th regard responsible consumption and production. The agritourism sector can promote green production efficiency by reducing the contamination of the environment and the generation of waste. There exists an important paradox: a tourist destroys what she/he is searching for, while she/he discovers it by consumption. In agro-tourism, special attention is required to the environment which constitutes the raw material, the subject, and the aim of tourism activity.

In this scenario, a territory rich in cultural heritage, like in this case Italian (Sicilian) one, can be the means *par excellence* to educate people about the beauty and raise the awareness of respect and protection of that territory. Moreover, the actual COVID-19 pandemic led to changes in habits and preferences.

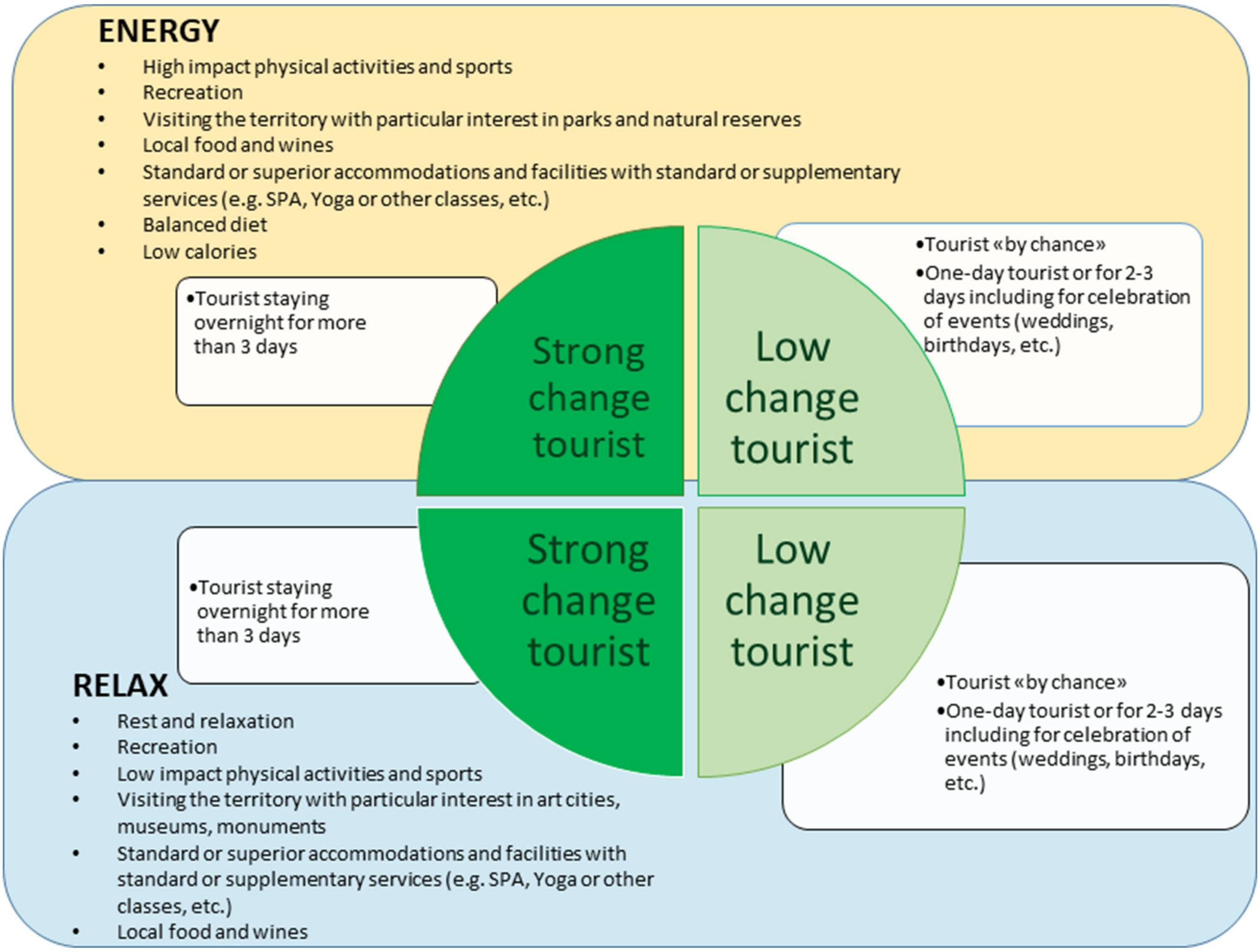


FIGURE 8
Agritourism tourists' profile regarding sustainable behaviors and holiday preferences.

From the results, tourists appeared to be more willing to make different travel choices after the healthcare crisis. They prefer to be involved in vacations away from crowded destinations, spending time in outdoor spaces immersed in nature and respecting the environment—and agritourism satisfies sufficiently this demand. In fact, according to results, the tourist need for a holiday regarding sustainability, outdoor activities, and spaces immersed in untouched nature can be satisfied by agritourism with an integrated tourism offer thanks to the combination of resources, services, and the structure itself; in brief, all the tangible and intangible cultural heritage. The beauty of the landscape merges with the tasting of local agricultural products and handicrafts, thus tourists can enjoy a sustainable holiday living different experiences, which goes from the overnight stay to cooking classes, workshops, relaxing SPAs, trekking, and visit to neighboring places. All of that, living an experience based on economic principles like reduction of waste through redesign, recycling, and reuse; minimum impact on air, water, and soil; and efficient use of natural resources and contribution to the economic development of host communities while preserving them at the same time.

In addition, it is important to underline that habits linked to the current economic model are not easy to set aside in favor of the circular one. It is evident from the fact that many tourists, while traveling, require the daily change of towels and affirm, "Comfort and quality-price ratio are more important than green practices"; on the other hand, they recognize the importance of green services and desire to produce the minimum possible pollution and to do zero-emission activities in a natural framework. From the point of view of entrepreneurs, agritourisms reveal a great rate of green activities and practices related to the circularity declaring to provide guests with information about the environmental compatibility of the business. For example, sustainable practices adopted are compost, separate collection of waste, solar panels installation, linen change in accordance with customers' needs, reuse of rainwater for compatible purposes, avoiding single-use products when possible, recyclable packages, and the vacuum to make and the use of detergents and disinfectants with environmental certificates. It appears interesting to find the high percentage of tourist interviewed who says that it is difficult to find tourism establishments implementing the circular model. In addition, they are not sure about Sicilian agritourisms with regard to the effective adoption of sustainable practices or measures related to the circular economy due to the lack of advertising, mostly.

The sustainable integrated offer embraces the economic, social, and environmental aspects of the concept of slow tourism. It implies a new way of living the time while traveling. Places are reached to be lived and to be protected at the same time, not only visited passively. Some authors (Bellia et al., 2021) describe slow tourism as the connection between the emotional vision and the sensitivity toward sustainability where tourists and excursionists choose holidays to be able to create a strong connection with the territory. Agritourism brings advantages such as an alternative source of income for the entrepreneur and their family, responsible management of natural resources with waste reduction, recycling and the maintenance of biodiversity, boost given to local economies and the enhancement of traditions, and education for visitors to the rural word with a return to a more sustainable lifestyle.

Findings highlighted the need to improve information and communication by farmhouses on their website, social networks, and inside the establishment itself. At the same time, it should be great to improve the spread of information about this new economic model starting with schools and training courses for entrepreneurs and employees, stepping up with a specific use of social media, which has a growing impact on our lives. Results show that there is still a significant portion of respondents who do not have an academic or correct knowledge of what the circular economy is.

The agritourist activity carried out in Italy initially aroused strong opposition from the hotel industry; today such frictions have largely receded thanks to regulatory refinements that are in some ways more open but substantially more rigorous and selective. Unluckily, most of the incentives are intended to promote mainly classic tourism businesses. Therefore, agritourisms invest more in tourist offers apart from farming ones. To get over this matter, the food supply chain can be improved thanks to specific funds to make a tourist offer that is natural, cultural, and healthy. From 2022 to 2024, lots of funds from the Italian National Restart and Resilience Plan (NRRP) were destinated to the tourist sector (and therefore to agritourisms) and this financing will certainly help farmers to make investments in more green and digital processes. Nevertheless, it is quite difficult for farmers to face the complexity of the procedure to access these funds. Fortunately, also the new CAP destinated lots of resources for these types of investments which are specifically suitable for farms. Also, in this case, it will be interesting to observe the effective accessibility and suitability of the measures that finance sustainable development in the regional Rural Development Plans for small firms of the rural disadvantaged areas of many EU territories, like Sicily in this case.

Therefore, after all this discussion, it is possible to conclude that agritourism can be an important means to convey sustainable behavior to people and tourists thanks to its fundamental role in this transition process. However, this sustainable development path must arise from the link between sustainability and economic, social, cultural, and environmental actions to avoid an asymmetric transition. At the same time, changes in people's lifestyles have brought tourists closer to preferring agritourism farms as providers of eco-sustainable ecosystem services. Shared aims and vision between farmers and visitors are the key elements wherein to build shared development policies based on environmental sustainability and marketing strategies for firms in the tourist sector. Due to its natural characteristics, agritourism can be an answer to a demand for a circular economy and sustainable tourism, and at the same time, it is also a catalyst able of intercepting subsidies under the agricultural and Next Generation EU Policies of the European Union (Figure 9).

To sum up, even if there are good possibilities for a green transition (in accordance with the EU Green Deal and the CAP aims), significant efforts are required by small farms in rural and disadvantaged areas of the Union. Funds are the basis to achieve the desired changes following policy decisions. Nevertheless, intervention tools for sustainable tourism should be based on a virtuous compromise between increasing competitiveness and controlling the pressures on social, territorial, and environmental systems. Moreover, Italian agritourisms may need help from consultants and experts to access the Italian NRRP funds because of the bureaucratic complexity to respond to public calls. However, agritourism may be the first tourist enterprise that embodies sustainable tourism. Certainly, Italian agritourisms might not be enough to satisfy the increasing offer of green, sustainable, and ethical tourism, because of the Law that limits farmers to privilege farming activity, and therefore they will remain a niche beside the larger offer of rural tourism. For this reason, they need the interest of territorial stakeholders and policymakers. They should be helped to easily access the funds and at the same time promote their precious activity for the territory. They are at the base of rural tourism, food & wine tourism, religious tourism, seasonal tourism, and cultural tourism of a region. Therefore, these activities must be supported at a local level to contribute to enhancing the territorial attractiveness.

5. Conclusion and limitations

The study attempts to provide a broader perspective of the actual situation in Sicily concerning the agritourism's green transition and the role of this type of tourist offer to facilitate the process of awareness and use of positive and sustainable behaviors in the tourist sector among people. Italy is the first European country for a number of farms engaged in organic farming, and southern regions cover a great position among Italian enterprises, which implemented sustainable decisions. Findings demonstrated that the EU agritourisms, in general, may be the main proponents of the green transitions for many reasons. In the first place, the farmhouses bring in themselves, by their very nature, the green transition, also because of the huge financial support of the new CAP aimed to promote structural investments that favor the application, at the firm level, of sustainable processes of resources' use, production, and disposal. These incentives will make this transition inevitable.

Second, agritourism is the guardian of the rural territory and the traditional agricultural landscape, and contributes to the improvement of its quality, in a sustainable perspective. In particular, the quality of air, water, and soil, the production of healthy food and clean energy, the promotion of the circular economy and sustainable mobility, the reduction of architectural

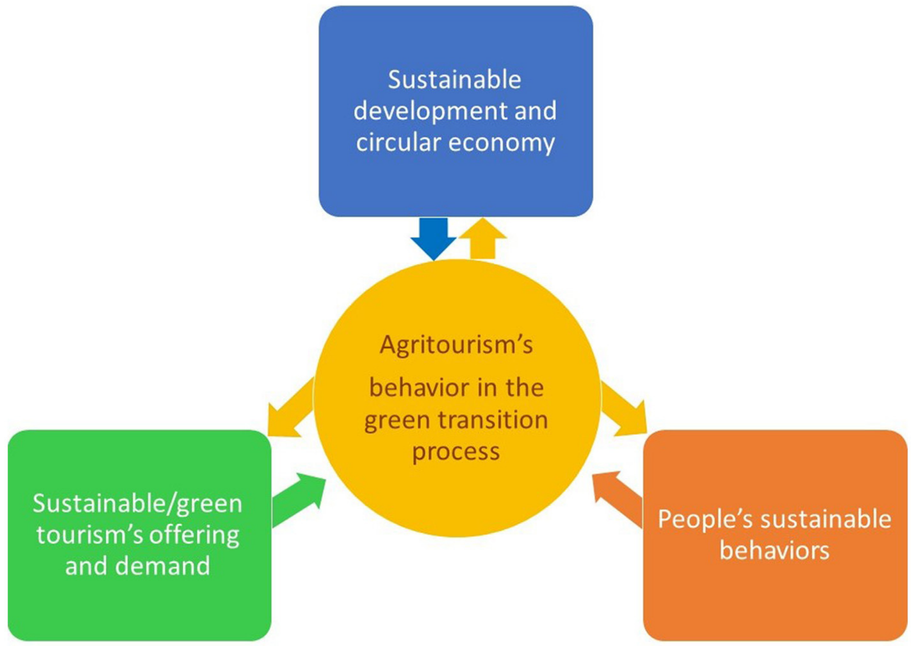


FIGURE 9
Influences among agritourism's and people's sustainable behaviors and sustainable economy and tourism.

barriers, and the animation of socio-economic exchanges among urban, suburban, and rural populations. Agritourism can offer low environmental impact activities that respect local communities, enhance the short supply chain, favor the application of rainwater reuse systems for compatible purposes, and so on.

In addition, the farm, besides being a supplier of quality food and ecosystem services, is also a promoter of healthy behavior and consumption of seasonal local food products by visitors, so it may be a vehicle for adopting the Mediterranean Diet as a lifestyle and sustainable food system.

Moreover, the growing propensity of people to search for ecological products and green services helps the farm to improve and orient itself with greater awareness toward the tourism sector, for more ethical, responsible, and sustainable tourism. In connection with this, outcomes show how important it would be for farmers to differentiate in multifunctionality, consisting of the mix of different offers and professional knowledge. This may help to change from mere farmers to aware tourism entrepreneurs that take care of their territory and exploit it considering it an added value (Bellia et al., 2022).

Finally, one of the most important points is a gradual change in mindset and this can only happen through effective communication, both a firm and institutional level, based on school seminars, tv educational advertising, and population educational campaigns.

In our opinion, the limit of this study is that it was carried out only in one Italian region, albeit representing southern Italy. To confirm the results that emerged both from the side of tourists and entrepreneurs, and validate the model of development of sustainable behavior, it would be interesting to repeat the study in other more developed agricultural regions of both northern Italy and Europe. Moreover, to confirm the results obtained, it would also be interesting to replicate the study in other disadvantaged agricultural regions of the EU where the effects of the application of the CAP deserve to be observed immediately. Finally, it would also be interesting to expand the study by observing the wider offer of rural tourism by those structures that today practice tourist reception activities in villages or rural areas while not being primarily agricultural enterprises at the end to understand if this type of tourist enterprises can be considered competitors of the farmhouses as such.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Written informed consent for participation was not required for this study in accordance with national legislation and institutional requirements.

Author contributions

MI: conceptualization, methodological design, supervision, validation, and revision of the manuscript until the final draft. MI and PC: study design. MI, MA, and SC: investigation. MA:

database organization and formal analysis. SC and CB: project administration and funding acquisition. Particularly, MI wrote the paragraphs: 1. Introduction (with exclusion of sub-paragraphs 1.1. Literature review, 1.2. Law review, 1.3. Brief history of Sicilian agriculture), 2. Materials and methods, 4. Discussion, 5. Conclusions and limitations. CB wrote: 1.1. Literature review. LA wrote: 1.2. Law review. SB wrote: 1.3. Brief history of Sicilian agriculture; of the paragraph 3. Results. SB and MI wrote: 3.1. Results of agritourisms analysis. MI wrote: 3.1.1. Focus on agritourism's green transition and sustainable behavior choices. SC wrote: 3.2. Results of tourist analysis. SC and MI wrote: 3.2.1. Focus on tourists' sustainable behavior and choices; finally, the proposed model shown in Figure 1 was developed by MI and SB; the Agritourism tourists' profile illustrated in Figure 8 was developed by MI and SC and the proposed model shown in Figure 9 was developed by MI. All authors contributed to writing-original draft preparation, read and agreed to the published version of the manuscript, and approved the submitted version.

Funding

This research was partially funded by Research Project Sostenibilitá Economica, Ambientale e Sociale del Sistema Agroalimentare del Mediterraneo, Principal investigator CB funded by Piano di Incentivi per la Ricerca di Ateneo (PIACERI) UNICT 2020/22 line 2, UPB: 5A722192154, University of Catania and also by the UNIPA-FFR2021 Stefania Chironi.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1174623/full#supplementary-material

References

Aguiñaga, E., Henriques, I., Scheel, C., and Scheel, A. (2018). Building resilience: a self-sustainable community approach to the triple bottom line. *J. Clean. Prod.* 173, 186–196. doi: 10.1016/j.jclepro.2017.01.094

Andersen, M. S. (2007). An introductory note on the environmental economics of the circular economy. *Sustain. Sci.* 2, 133–140. doi: 10.1007/s11625-006-0013-6

Bacarella, A. (2021). *Storia moderna dell'agricoltura siciliana: dall'anteguerra ai giorni nostri*. Vol. 1–2. Palermo: La Zisa

Badami, A. A. (2021). Managing the historical agricultural landscape in the sicilian anthropocene, context and the landscape of the valley of the temples as a time capsule. *Sustainability* 13, 4480. doi: 10.3390/su13084480

Bellia, C., Columba, P., and Ingrassia, M. (2022). The brand–land identity of Etna Volcano valley wines: a policy delphi study. *Agriculture* 12, 811. doi: 10.3390/agriculture12060811

Bellia, C., and Pilato, M. (2014). Competitiveness of wine business within green economy: Sicilian case. *Qual. Acc. Success* 138, 74–78.

Bellia, C., Scavone, V., and Ingrassia, M. (2021). Food and religion in Sicily—a new green tourist destination by an ancient route from the past. *Sustainability* 13, 6686. doi: 10.3390/su13126686

Benedetto, G., and Giordano, A. (2008). Sicily. *Mediterranean Island Lands. Nat. Cult. Approach.* 9, 117–142. doi: 10.1007/978-1-4020-5064-0_7

Bocken, N. M., De Pauw, I., Bakker, C., and Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. *J. Indus. Prod. Eng.* 33, 308–320. doi: 10.1080/21681015.2016.1172124

Boulding, K. E. (1966a). The economics of knowledge and the knowledge of economics. *Am. Econ. Rev.* 56, 1–13.

Boulding, K. E. (1966b). *The economics of the coming spaceship earth*. In: Jarrett, H., editor. *Environmental Quality in a Growing Economy*. Baltimore: The Johns Hopkins Press. p. 3–14.

Bresciani, F., Dévé, F. C., and Stringer, R. (2004). "The multiple roles of agriculture in developing countries," in *Sustaining Agriculture and the Rural Economy: Governance, Policy and Multifunctionality*. p. 286-306.

Charonis, G. K. (2012). "Degrowth, steady state economics and the circular economy: three distinct yet increasingly converging alternative discourses to economic growth for achieving environmental sustainability and social equity," in *World Economic Association Sustainability Conference*, Vol. 24. p. 1–18.

Chironi, S., Bacarella, S., Altamore, L., Columba, P., and Ingrassia, M. (2021). Consumption of spices and ethnic contamination in the daily diet of Italians-consumers' preferences and modification of eating habits. *J. Ethnic Foods* 8, 1–16. doi: 10.1186/s42779-021-00082-8

Curtis, K. R., and Slocum, S. L. (2016). The role of sustainability certification programs in reducing food waste in tourism. *J. Dev. Sustain. Agri.* 11, 1–7.

Darău, A. P., Corneliu, M., Brad, M. L., and Avram, E. (2010). *The Concept of Rural Tourism and Agritourism*. Arad: Studia Universitatis "Vasile Goldis". p. 39–42.

Ecker, S., Clarke, R., Cartwright, S., Kancans, R., Please, P., and Binks, B. (2010). *Drivers of Regional Agritourism and Food Tourism in Australia*. Available online at: https://apo.org.au/sites/default/files/resource-files/2010-01/apo-nid150976.pdf (accessed February 22, 2023).

Edizioni Europee (2023a). *Legge 5 dicembre 1985, n. 730. Disciplina dell'agriturismo*. Available online at: http://www.edizionieuropee.it/law/html/89/zn96_02_019.html (accessed February 23, 2023).

Edizioni Europee (2023b). *L. 20 febbraio 2006, n. 96. Disciplina dell'agriturismo*. Available online at: http://www.edizionieuropee.it/law/html/90/zn96_02_033.html (accessed February 23, 2023).

EU (2015). *Closing the Loop - An EU Action Plan for the Circular Economy COM/2015/0614 Final*. Available online at: https://www.eea.europa.eu/policy-documents/com-2015-0614-final (accessed February 22, 2023).

European Commission. (2010). *On the European Union's Humanitarian Aid and Civil Protection Policies and Their Implementation*. European Commission. Available online at: https://ec.europa.eu/echo/files/media/publications/annual_report/annual_report_2010.pdf (accessed February 26, 2023).

European Commission. (2015). *Sustainable Development in the European Union*. Available online at: https://ec.europa.eu/eurostat/documents/3217494/6975281/KS-GT-15-001-EN-N.pdf (accessed February 25, 2023).

European Environment Agency (1998). *Europe's Environment*: The second assessment. Amsterdam: Elsevier Science Limited.

European Parliament (2015). *Economia circolare: definizione, importanza e vantaggi*. Available online at: https://www.europarl.europa.eu/news/it/headlines/economy/20151201STO05603/economia-circolare-definizione-importanza-e-vantaggi (accessed February 24, 2023).

Geissdoerfer, M., Morioka, S. N., de Carvalho, M. M., and Evans, S. (2018). Business models and supply chains for the circular economy. *J. Clean. Prod.* 190, 712–721. doi: 10.1016/j.jclepro.2018.04.159

Geissdoerfer, M., Savaget, P., Bocken, N. M., and Hultink, E. J. (2017). The circular economy–a new sustainability paradigm? *J. Clean. Prod.* 143, 757–768. doi: 10.1016/j.jclepro.2016.12.048

Geng, Y., and Doberstein, B. (2008). Developing the circular economy in China: Challenges and opportunities for achieving 'leapfrog development'. *Int. J. Sustain. Dev. World Ecol.* 15, 231–239. doi: 10.3843/SusDev.15.3:6

George, D. A., Lin, B. C. A., and Chen, Y. (2015). A circular economy model of economic growth. *Environ. Model. Softw.* 73, 60–63. doi: 10.1016/j.envsoft.2015.06.014

Ghisellini, P., and Ulgiati, S. (2020). Circular economy transition in Italy. Achievements, perspectives and constraints. *J. Clean. Prod.* 243, 118360. doi: 10.1016/j.jclepro.2019.118360

Gómez, M., and Martinez, M. M. (2023). Redistribution of surplus bread particles into the food supply chain. *LWT* 173, 114281. doi: 10.1016/j.lwt.2022.114281

Hamel, P. (2011). *Breve storia della società siciliana, 1790-1980*. Palermo: Sellerio.

Iannetta, M., and Padovani, L. M. (2015). *La Dieta Mediterranea: modello di consumo sostenibile a ridotto impatto ambientale.* Available online at: https://www.enea.it/it/seguici/pubblicazioni/pdf-eai/speciale-eneaxexpo/dieta-mediterranea-modello-di-consumo.pdf (accessed February 22, 2023).

Ingrassia, M., Altamore, L., Bellia, C., Grasso, G. L., Silva, P., Bacarella, S., et al. (2022a). Visitor's motivational framework and wine routes' contribution to sustainable agriculture and tourism. *Sustainability* 14, 12082. doi: 10.3390/su141912082

Ingrassia, M., Chironi, S., Lo Grasso, G., Gristina, L., Francesca, N., Bacarella, S., et al. (2022b). Is environmental sustainability also "Economically Efficient"? The case of the "SOStain" certification for sicilian sparkling wines. *Sustainability* 14, 7359. doi: 10.3390/su14127359

ISTAT (2023a). Available online at: http://dati.istat.it/# (accessed May 31, 2023).

ISTAT (2023b). Available online at: https://www.istat.it/it/archivio/277798 (accessed February 14, 2023).

Kachniewska, M. A. (2015). Tourism development as a determinant of quality of life in rural areas. *Worldwide Hosp. Tourism Theme.* 7, 500–515. doi: 10.1108/WHATT-06-2015-0028

Keränen, O., Lehtimäki, T., Komulainen, H., and Ulkuniemi, P. (2023). Changing the market for a sustainable innovation. *Indust. Market. Manag.* 108, 108–121. doi: 10.1016/j.indmarman.2022.11.005

Kim, S., Lee, S. K., Lee, D., Jeong, J., and Moon, J. (2019). The effect of agritourism experience on consumers' future food purchase patterns. *Tour. Manag.* 70, 144–152. doi: 10.1016/j.tourman.2018.08.003

Kirchherr, J., Reike, D., and Hekkert, M. (2017). Conceptualizing the circular economy: an analysis of 114 definitions. *Resour. Conserv. Recycl.* 127, 221–232. doi: 10.1016/j.resconrec.2017.09.005

Korstanje, M. E., and George, B. P. (2020). "Education as a strategy to tackle over tourism for overtourism and inclusive sustainability in the twenty-first century," in *Overtourism: Causes, Implications and Solutions.* p. 341–359. doi: 10.1007/978-3-030-42458-9_18

MacArthur Foundation and Google (2019). *Artificial Intelligence and the Circular Economy: AI as a Tool to Accelerate the Transition.* Available online at: https://www.mckinsey.com/business-functions/sustainability/our-insights/artificial-intelligence-and-the-circular-economy-ai-as-a-tool-to-accelerate-the-transition

Macarthur Foundation. (2013). *What is a Circular Economy?* Available online at: https://www.mckinsey.com/capabilities/sustainability/our-insights/artificial-intelligence-and-the-circulareconomy-ai-as-as-a-tool-to-accelerate-the-transition (accessed February 18, 2023).

Markose, N., Vazhakkatte Tazhathethil, B., and George, B. (2022). Sustainability initiatives for green tourism development: the case of Wayanad, India. *J. Risk Finan. Manag.* 15, 52. doi: 10.3390/jrfm15020052

McKinsey. (2022). *No Time to Waste: What Plastics Recycling Could Offer.* Available online at: https://www.mckinsey.com/industries/chemicals/our-insights/no-time-to-waste-what-plastics-recyclingcould-offer (accessed December 15, 2022).

Melo Ribeiro, H. C., and de Souza, M. T. S. (2022). Economía circular y turismo: producción científica a la luz de un análisis de redes sociales. *Estudios Gerenciales* 38, 385–402. doi: 10.18046/j.estger.2022.164.5086

Merli, R., Preziosi, M., and Acampora, A. (2018). How do scholars approach the circular economy? A systematic literature review. *J. Clean. Product.* 178, 703–722. doi: 10.1016/j.jclepro.2017.12.112

Murray, A., Skene, K., and Haynes, K. (2017). The circular economy: an interdisciplinary exploration of the concept and application in a global context. *J. Busin. Ethics* 140, 369–380. doi: 10.1007/s10551-015-2693-2

Nocca, F., Bosone, M., De Toro, P., and Fusco Girard, L. (2023). Towards the human circular tourism: recommendations actions, and multidimensional indicators for the tourist category. *Sustainability* 15, 1845. doi: 10.3390/su15031845

Pappalardo, G., Sisto, R., and Pecorino, B. (2018). Is the partnership governance able to promote endogenous rural development? A preliminary assessment under the Adaptive Co-management approach. *Eur. Countryside* 10, 543–565. doi: 10.2478/euco-2018-0031

Pearce, D. W., and Turner, R. K. (1990). *Economics of Natural Resources and the Environment*. Baltimore: The Johns Hopkins University Press.

Pedrotti, M., Daniele, F., Marta, A., and Bob, C. (2023). Approaching urban food waste in low- and middle-income countries: a framework and evidence from case studies in Kibera (Nairobi) and Dhaka. *Sustainability* 15, 3293. doi: 10.3390/su15043293

Phelan, C., and Sharpley, R. (2011). Exploring agritourism entrepreneurship in the UK. *Tour. Plann. Dev.* 8, 121–136. doi: 10.1080/21568316.2011.573912

Pollard, S., Turney, A., Charnley, F., and Webster, K. (2016). The circular economy–a reappraisal of the 'stuff'we love. *Geography* 101, 17–27. doi: 10.1080/00167487.2016.12093979

Renda, F. (2003). *Storia della Sicilia dalle origini ai giorni nostri.* 3 voll. Palermo: Sellerio.

Renting, H., Rossing, W. A., Groot, J. C., Van der Ploeg, J. D., Laurent, C., Perraud, D., et al. (2009). Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. *J. Environ. Manag.* 90, S112–S123. doi: 10.1016/j.jenvman.2008.11.014

Rodríguez, C., Florido, C., and Jacob, M. (2020). Circular economy contributions to the tourism sector: a critical literature review. *Sustainability* 12, 4338. doi: 10.3390/su12114338

Safonte, G. F., Bellia, C., and Columba, P. (2021). Commoning of territorial heritage and tools of participated sustainability for the production and enhancement of agro-environmental public goods. *Agricult. Food Econ.* 9, 1–20. doi: 10.1186/s40100-021-00180-w

Santucci, F. M. (2013). Agritourism for rural development in italy, evolution, situation and perspectives. *J. Econ. Manag. Trade* 3, 186–200. doi: 10.9734/BJEMT/2013/3558

Scheepens, A. E., Vogtländer, J. G., and Brezet, J. C. (2016). Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable. *J. Clean. Prod.* 114, 257–268. doi: 10.1016/j.jclepro.2015.05.075

Selvaggi, R., and Valenti, F. (2021). Assessment of fruit and vegetable residues suitable for renewable energy production: GIS-based model for developing new frontiers within the context of circular economy. *Appl. Syst. Innov.* 4, 10. doi: 10.3390/asi4010010

Sisto, R., Cappelletti, G. M., Bianchi, P., and Sica, E. (2022). Sustainable and accessible tourism in natural areas: a participatory approach. *Current Issues Tour.* 25, 1307–1324. doi: 10.1080/13683500.2021.1920002

Streifeneder, T., and Dax, T. (2020). Agritourism in Europe: enabling factors and current developments of sustainable on-farm tourism in rural areas. In: *Global Opportunities and Challenges for Rural and Mountain Tourism.* Hershey, PA: IGI Global. p. 40–58.

United Nations (1993). *Integrated Environmental and Economic Accounting: Interim Version, Handbook of National Accounting (interim version).* New York, NY: United Nations.

United Nations (2003). *European Commission, International Monetary Fund, Organization for Economic Co-operation and Development, and World Bank, Handbook of National Accounting: Integrated Environmental and Economic Accounting.* New York, NY: United Nations.

Whitfield, S., Challinor, A. J., and Rees, R. M. (2018). Frontiers in climate smart food systems: outlining the research space. *Front. Sustain. Food Syst.* 2, 2. doi: 10.3389/fsufs.2018.00002

Woodward, R. (2004). The organisation for economic cooperation and development: global monitor. *N. Pol. Econ.* 9, 113–127. doi: 10.1080/1356346042000190411

Yang, Z., Cai, J., and Sliuzas, R. (2010). Agro-tourism enterprises as a form of multi-functional urban agriculture for peri-urban development in China. *Habitat Int.* 34, 374–385. doi: 10.1016/j.habitatint.2009.11.002

Yuan, Z., Bi, J., and Moriguichi, Y. (2006). The circular economy: a new development strategy in China. *J. Indust. Ecol.* 10, 4–8. doi: 10.1162/108819806775545321

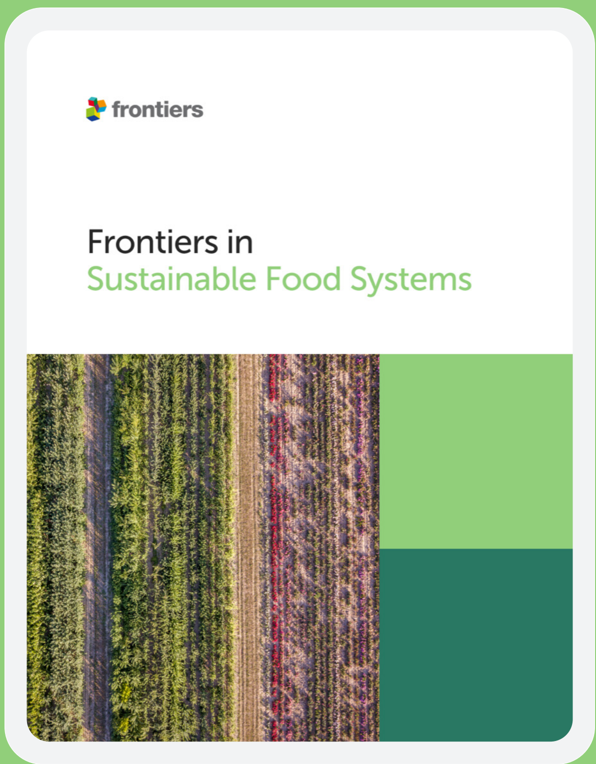
Frontiers in
Sustainable Food Systems

Exploring sustainable solutions to global food security

Aligned with the UN Sustainable Development Goals, this journal explores the intersection of food systems, science and practice of sustainability including its environmental, economic and social justice dimensions.

Discover the latest Research Topics

See more →



Frontiers

Avenue du Tribunal-Fédéral 34
1005 Lausanne, Switzerland
frontiersin.org

Contact us

+41 (0)21 510 17 00
frontiersin.org/about/contact