Research Topics

Pushing the Frontiers of nutritional Life Cycle Assessment (nLCA) to identify globally equitable and sustainable agri-food systems

Edited by
Ty Beal, Graham A. McAuliffe, Jolieke Van Der Pols
and Michael Lee

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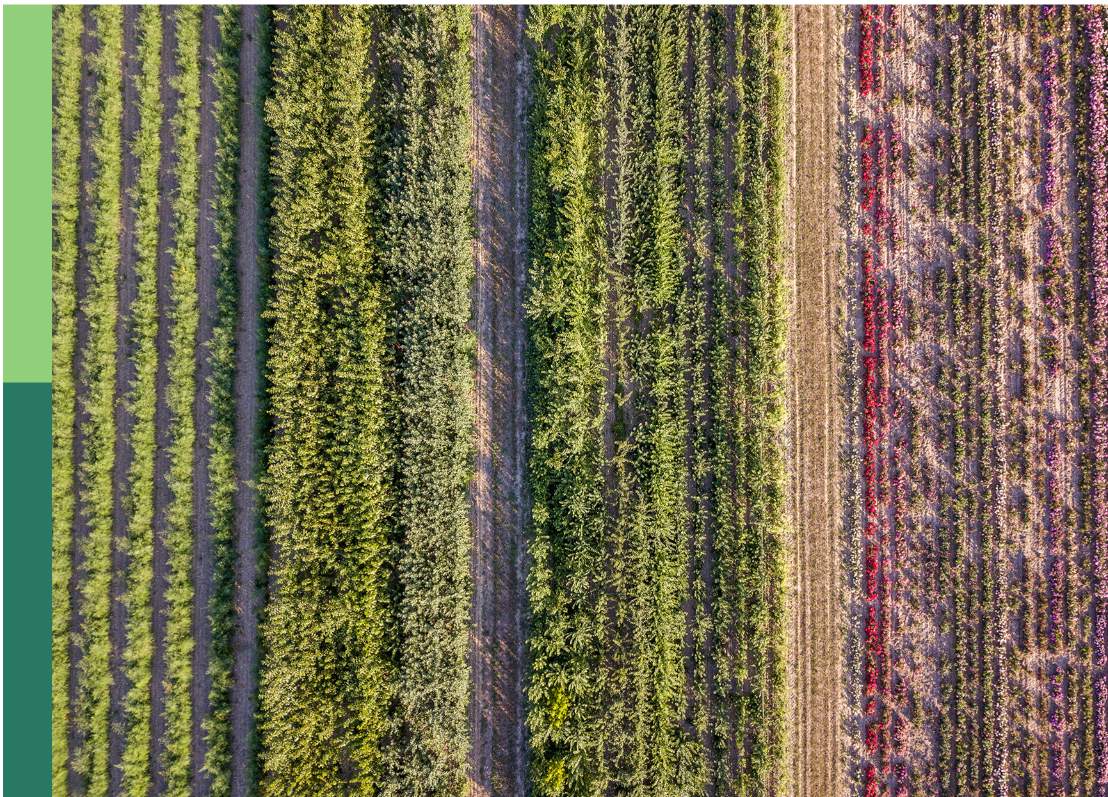

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Pushing the Frontiers of nutritional Life Cycle Assessment (nLCA) to identify globally equitable and sustainable agri-food systems

Topic editors

Ty Beal — Global Alliance for Improved Nutrition (GAIN), Switzerland
Graham A. McAuliffe — Harper Adams University, United Kingdom
Jolieke Van Der Pols — Queensland University of Technology, Australia
Michael Lee — Harper Adams University, United Kingdom

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Barbara Burlingame,
Massey University, New Zealand

*CORRESPONDENCE
Graham A. McAuliffe
gmcauliffe@harper-adams.ac.uk

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Editorial: Pushing the Frontiers of nutritional Life Cycle Assessment (nLCA) to identify globally equitable and sustainable agri-food systems

Graham A. McAuliffe[1]*, Ty Beal[2,3], Michael R. F. Lee[1] and Jolieke C. van der Pols[4]

[1]Harper Adams University, Newport, United Kingdom, [2]Global Alliance for Improved Nutrition (GAIN), Washington, DC, United States, [3]Institute for Social, Behavioral and Economic Research, University of California, Santa Barbara, Santa Barbara, CA, United States, [4]Faculty of Health, School of Exercise & Nutrition Sciences, Queensland University of Technology, Brisbane, QLD, Australia

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Editorial on the Research Topic
Pushing the Frontiers of nutritional Life Cycle Assessment (nLCA) to identify globally equitable and sustainable agri-food systems

Introduction

Life Cycle Assessment (LCA) has been applied to food supply chains for decades to identify environmental "hotspots" where action needs to be taken to reduce pollutants of interest or optimize land/resource use as defined under a study's goal and scope definition. The framework is also highly informative for decision making discussions when, e.g., comparing two or more systems performing the same function. Hypothetically speaking, such models may elucidate sustainability-related ramifications of changing ingredients in a food item across relevant environmental indicators (known as "impact categories"), often resulting in trade-offs whereby one system may generate more greenhouse gas (GHG) emissions, whilst another system may generate the same GHG emissions but demonstrate less water pollution. As alluded to, such comparative-based studies are assessed using the same "functional units" (scaling factors intended to represent the *function* of a product or service). In agri-food LCAs, functional units are commonly reported in the form of mass, volume or area at a system boundary's point of exit, often at the point of leaving the farm (cradle-to-gate). As environmental awareness is rapidly increasing globally, sustainability-related scientific research questions are targeting the consumer-facing side of food systems (cradle-to-plate). As a result, decisions made at the point of sale cannot be reliably informed using mass, volume or area alone; hence, nutritional LCA (nLCA; McLaren et al., 2021) has emerged as a sub-framework of LCA exploring the environment-nutrition nexus. Broadly speaking, nLCA can be broken down into three tiers pending a study's goal (McAuliffe et al., 2020): (1) single or multiple *individual* nutrients as functional units (McAuliffe et al., 2023; Saarinen et al., 2017); (2) adopting *composite* nutritional metrics (Katz-Rosene et al., 2023); (3) augmenting one or both of the first two tiers with the *direct* effect of a system's impact to human, or indeed planetary health (e.g., potential rises or falls in non-communicable diseases or species abundance, respectively). This additional layer of complexity is often assessed through the development of novel end-point impact assessments (LCIAs) and *multi-level* trade-off analyses, naturally making interpretation of such studies challenging (Ortenzi et al., 2023; Stylianou et al., 2016, 2021).

Building upon the brief introduction to nLCA hitherto, the sub-framework's evolution is reliant on multidisciplinary collaborations which, for simplicity, are described in the present editorial under four broad yet overlapping topics: functional units; nutritional complexities; data availability; and future directions. This editorial introduces 12 articles which, collectively, demonstrate how nLCA is evolving into a multi-faceted sustainability assessment framework that is highly informative for *consumers*, relative to, e.g., *producers*, the former of whom are arguably the most important food-system stakeholders under cradle-to-plate system boundaries. As will become clear in the subsequent sections, certain articles in this novel compendium on nLCA are applied case studies showcasing the method's capabilities, whilst others propose methodological advancements or considerations. The "data availability" and "future directions" sections draw the reader's attention to another branch of articles which raise awareness of beneficial issues to the progression of nLCA, or further, provide novel data and/or information to do so.

Nutritional LCA functional units

"Nutritional functional units" have been adopted for well over a decade by reporting LCIAs based on, e.g., energy (kcal/mass unit) or protein (g/mass unit) content in agri-food commodities, thus preceding the *formal* development and subsequent rise of nLCA. Given the importance of functional units when answering specific research questions (i.e., goal and scope definitions), they have perhaps received the most methodological attention in literature surrounding "pushing the frontiers of nLCA," both *within* the current Research Topic *and* beyond. Apart from utilizing individual nutrients (quite commonly total protein as demonstrated by Poore and Nemecek, 2018b, a nutrient with limitations of its own discussed elsewhere; McAuliffe et al., 2023) the most common way of transforming functional units into a nutritional lens is via utilization of composite nutritional scores such as the Nutrient Rich Food (NRF) index as proposed by Fulgoni et al. (2009). At the simplest level, using NRF or similar nutritional metrics as a functional unit standardizes the nutritional content of a food against the recommended intake levels in a target population (thus offering the benefit of being able to consider differences in nutritional requirements between different population groups) for a range of nutrients, including nutrients to promote and nutrients to limit, when assessing a food's environmental footprint (Majumdar et al.). Countless authors have developed bespoke variations of the NRF-style approach (see McAuliffe et al., 2020), but one novel and interesting approach stands out within the current Research Topic by Majumdar et al.. The authors applied composite-based nutritional functional units to a "toppings on toast" case study, to evaluate the effect of NRF choice (9 vs. 28 nutrients to encourage) when assessing climate change impact of different toast topping options. This novel adoption of nLCA is interesting not only to developers/practitioners, but also consumers worldwide given the global applicability of using toppings on food (e.g., condiments), not just toast.

McNicol et al. build upon and evolve earlier, simpler work conducted alongside the development of the UK Nutritional Index (UKNI; McAuliffe et al., 2018) by focussing on long-chain polyunsaturated fatty acids (specifically omega-3 fatty acids) as individual nutritional functional units. The study represented sheep production systems in the UK, with inventory analyses conducted using a combination of primary, farm-level data and a commercial process-based model for calculating GHG emissions. Also important to note, both McNicol et al. and Wingett and Alders add to sustainability literature of ovine production systems, with the latter focussing upon nutrient losses from Australian supply chains, strengthening the overall contribution to (n)LCA literature contained within the present Research Topic.

Whilst Cardinaals et al. present an interesting discussion on the strengths and weaknesses of various approaches to nLCA, including complexities surrounding functional units, their study is more nutritionally complex than other (n)LCAs and thus covered in more detail in the next section. The compendium of articles introduced here also includes a useful bibliographic resource in the form of a "mini review" on bakery products, whereby Cassarino et al. also consider methodological considerations of waste in nLCA, an understudied yet emerging topic of interest.

Nutritional complexities and associated uncertainties

Foods contain thousands of compounds, most of which scientists have limited understanding of, especially with respect to how they interact and form complex matrices (Barabási et al., 2020). Diverse genetic characteristics, as well as variability in nutritional, developmental and health status across individuals further complicate our ability to understand how specific foods and nutrients impact human health (Stover and Caudill, 2008). Limitations relating to availability of reliable food composition data and nutritional intake estimation also hinder the implementation of scientific best practices in nLCA, as demonstrated in this editorial and associated articles. These factors collectively explain the significant challenges in quantifying the nutritional *quality* of foods for use in nLCA.

Articles in this Research Topic highlight several key aspects of nutritional complexity in nLCA. Cardinaals et al. demonstrate that nutrient density and the estimated disease burden associated with a food complement each other as measures of nutritional quality, emphasizing the need for comprehensive approaches that consider both nutrient content and health impacts in line with global expert recommendations (Scherer et al., 2024). Cassarino et al. underscore the importance of incorporating factors like satiety and the need to consider both beneficial and harmful aspects of foods, suggesting integrated indices as a means to provide a more complete picture of a food's nutritional impact. Majumdar et al. identify significant variability and uncertainty in nutritional impacts due to factors such as production practices, food varieties, and population-specific contexts, advocating for flexible, context-sensitive approaches in nLCA. These findings collectively point to the multifaceted nature of nutritional assessment(s) in LCA and stress the importance of considering a wide range of factors to accurately capture food's nutritional value.

The key research gaps highlighted by these studies center on the need for more comprehensive approaches to capture the full complexity of nutritional impacts in LCA. This includes improving our understanding of nutrient bioavailability and interactions within food matrices, long-term health impacts of dietary patterns, and population-specific nutritional effects. There is also a need for better methods to quantify and integrate both beneficial *and* potentially harmful aspects of foods, as well as physiological responses like satiety and social impacts associated with purchasing (e.g., rural/community-based "localness") and improvements to mental health via "family mealtime," for instance. Additionally, researchers face challenges in scaling up assessments from individual foods to capture broader diets (or indeed dietary changes and associated yet unintended consequences) and food system levels while *maintaining* the accuracy and relevance expected from environmental LCAs under international standards such as ISO 14044. Addressing these gaps, perhaps via formal standard development, could improve the ability of nLCA to provide more complete pictures of cross-pillar agri-food sustainability assessments considering nutritional dimensions.

Data availability and geographical representation

Whilst this Research Topic of publications cannot in any degree be considered representative of nLCA literature overall, a brief scan of scientific repositories will largely concur with the reality that, until recently, most contributions to cutting-edge sustainability assessments occur in, and/or focus on, high income countries, an observation bolstered by Poore and Nemecek (2018a). This is by no means a novel observation, e.g., see table 1 in Roy et al. (2009), but it indicates an element of data-based stagnation manifesting as a barrier restricting *rapid* expansion of nLCA to low- and middle-income countries where: (a) it is potentially more societally impactful as more is already known about the environment-nutrition nexus in high-income countries, and (b) there are anecdotally-indicative demands for novel, sustainability-focussed research projects evidenced by recent efforts to achieve this (Kamudoni et al., 2024; Ndung'u et al., 2022). The present Research Topic goes some way to breaching geographical representation barriers by offering crucial data to directly inform nLCAs, or, at the very least, develop locally specific, detailed goal and scope definitions. For instance, Duvivier et al. use social science methods (a mix of quantitative surveys and qualitative interviews) to identify localized issues such as gender inequalities and associated health statuses between male and female farmers in Haiti. This approach provides (n)LCA scientists with the foundations to follow up with a cross-pillar (i.e., environment-economic-nutrition/health) system-scale analysis, not dissimilar in data-driven impact potentials offered by Sarma et al. in Bangladesh.

Granados-Echegoyen et al. provide more direct nutritional data on a highly topical subject: edible insects. The authors not only provide broad nutritional values of native insects in multiple nations across Latin America and the Caribbean, they also provide detailed amino acid and fatty acid profiles, as well as antinutrient factors, all of which combined lay a pathway to fulfilling previous recommendations surrounding fatty acid and amino acid complexities (McAuliffe et al., 2018, 2023) by developing or enhancing sophisticated nutritional metrics, with the Nutritional Value Score (NVS; Beal and Ortenzi, 2023) being one such holistic example.

Future directions for nLCA

Although not all articles presented as part of this Research Topic ("Pushing the Frontiers of Nutritional Life Cycle Assessment") are nLCAs themselves, each one contributes to the scope *and* capability of nLCA, either geographically speaking or via methodological innovations; thus, this Research Topic improves the efficacy of decision-making based on such studies. Due to available space, each article was not discussed in detail herein; nevertheless, as presented in this brief introduction to the Research Topic, aforementioned enhancements to scope and efficacy arise from three broad topics: (1) novel functional units or discussions thereof; (2) nutritional complexities which require attention by LCA scientists through collaboration with expert colleagues in the nutrition, health, and social sciences; and (3) data restrictions and routes to overcome them, each of which is addressed by this novel compendium. Further, it is important to acknowledge that each of the topics are interlinked. For instance, data restrictions may be summarized from both an environmental perspective and a nutritional perspective as follows: (i) environmentally speaking, poor geographical coverage of low- and middle-income countries' inventory compilation data, as well as understandings of local/regional agricultural, cultural, and cooking uniqueness all need to be improved in terms of data transformations and model interpretations; (ii) Improving nLCA through a nutritional science lens is more challenging, as the issues are known (e.g., differences in product quality arising from digestibility and bioavailability of individual nutrients), but are incredibly difficult to measure. However, as our understanding improves from what experimental data *already* exists, metrics such as the NVS (Beal and Ortenzi, 2023) are, in time, going to produce more insightful messages via nLCA. With the above issues in mind, the guest editorial team hopes you see the value of each of the studies included herein and enjoy reading them. More importantly, the team hopes the Research Topic inspires future nLCAs, regardless of whether methodologically-focussed or the development of new research questions, which would not only fill gaps in the current evidence base, but also aid consumers in making more environmentally friendly and simultaneously nutritionally beneficial decisions at the point of sale.

Author contributions

GM: Conceptualization, Project administration, Validation, Writing – original draft, Writing – review & editing. TB: Project administration, Validation, Writing – original draft, Writing – review & editing. ML: Project administration, Validation, Writing – review & editing. JP: Project administration, Validation, Writing – review & editing.

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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.

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EDITED BY
Jolieke Van Der Pols,
Queensland University of Technology, Australia

REVIEWED BY
Babak Pakbin,
Technical University of Munich, Germany
Wageh Darwish,
Zagazig University, Egypt

*CORRESPONDENCE
Daniela-Mihaela Grigore
✉ daniela-mihaela.grigore@usamv.ro
Ioan Pet
✉ ioanpet@usab-tm.ro

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Screening and detection of antibiotic residues on broiler meat based on trade system variations, seasonal differences, and the impact on final consumer safety in Romania

Elena Narcisa Pogurschi[1], Daniela-Mihaela Grigore[1]*, Daniela Ianitchi[1], Gratziela Bahaciu[1], Dana Catalina Popa[1], Nela Dragomir[1] and Ioan Pet[2]*

[1]Department of Food Sciences, Faculty of Animal Productions Engineering and Management, University of Agronomic Sciences and Veterinary Medicine of Bucharest, Bucharest, Romania, [2]Department of Biotechnologies, Bioengineering Faculty of Animal Resources, Banat University of Agricultural Science and Veterinary Medicine "King Michael I of Romania", Timisoara, Romania

Introduction: One key factor contributing to microbial resistance is the deliberate and inappropriate use of antibiotics in human and animal health management. Recent studies point out various ways to tackle this controversy to mitigate the unnatural rapid evolution of pathogenic bacteria. Chicken meat remains at the top of Romanian consumers' preferences, being the most consumed type of meat, desired for its nutritional and dietetic attributes.

Methods: This research was conducted in 2022, aiming to evaluate the antibiotic residues (quinolones, aminoglycosides, tetracycline, and sulfonamides) in broiler chicken meat with various trade strategies [retail market (RM), $n = 40$, traditional market (TM), $n = 185$, and door-to-door vendors (DTD), $n = 121$] during two seasonal periods, spring (March–April) and summer (July–September). An efficient and precise protocol was employed for determining the meat organoleptic attributes, qualitative screening, and quantitative assay antibiotic of six antibiotics (enrofloxacin, marbofloxacin, streptomycin, oxytetracycline, doxycycline, and sulfamethoxazole), consumers' antibiotic exposure (estimated daily intake), and potential risk assessment (hazard quotient).

Results: The antibiotic quality assessment revealed an overall antibiotic residue presence in groups TM (75%) and DTD (82%), while no antibiotic residues were detected in the RM group. Our results show that 32% ($n = 110$) of the total chicken meat samples were free of antibiotic residues, 4.5% ($n = 16$) contained antibiotic residues belonging to one class of antibiotics, 40% ($n = 139$) had two antibiotics groups, 22% ($n = 77$) had three antibiotics groups, and 1.5% of the chicken meat samples presented four groups of antibiotics.

Discussion: During the spring season, the enrofloxacin antibiotic residue present in the meat samples was higher, showing an 84% presence in TM meat samples group when compared with the DTD meat sampled group (75%). The analysis data processing showed a strong correlation between the antibiotic residue's meat samples origin (trade market and door-to-door traded meat antibiotic residue variations) and seasonal variations. As a result of the hazard quotient assay, the meat antibiotic residue levels had subunit values, indicating the meat quality was proper for consumption. It is mandatory to strengthen the level of knowledge by continuously monitoring and providing updated information to each group of farmers to increase their understanding of and adherence to the proper handling of antibiotics when growing chickens. Regarding the use of prohibited growth-promoting antibiotics in chicken-rearing systems, local authorities should increase the guard level, at antibiotic supplier and end user levels.

KEYWORDS

antibiotic resistance, food safety, meat antibiotic residue, public health, the withdrawal period

1. Introduction

Chicken meat has been by far the most appreciated dietary animal protein among Romanian consumers (Balan et al., 2022), placing the poultry sector on top of the meat-producing industries in the last year, with around 550kt of meat sold (as carcass) (INSSE, 2023). Moreover, the chicken meat-producing systems' trend toward environmentally friendly and high-quality products (Barbut and Leishman, 2022), while recirculating waste and increasing productivity (Boumans et al., 2022), has also increased their popularity. However, extrinsic quality parameters (production, processing, and marketing) present a major role in perception, expectation, and consumers' purchase decisions. The Romanian consumer's purchase decision behavior (in the retail market and out of it) regarding poultry meat quality is affected by two main factors, first is the employed farming techniques (Pirvutoiu and Popescu, 2013) and the second is the affordability of meat price (Caratus Stanciu, 2020). Poultry meat that originates from small-size farming (semi-intensive rearing systems) is often merchandised in traditional markets and local fairs at a much higher price than conventionally reared chickens, having a specific customer-targeted group of young people and the elderly (Voinea et al., 2020) due to their high-quality attributes (Grigore et al., 2023). Another available marketing source of broiler chicken meat is individual producers either via door-to-door vendors or internet advertisement, generally offering "home-made" chicken meat (extensive reared system). While conventional, semi-intensive, or extensive farming systems are facing common challenges such as prolonged infectious threats (Pandey and Kumar, 2021), it is difficult to establish the boundary between welfare, health safety practices, and consumer risks (Berg, 2001). A common practice, often employed in broiler rearing systems, is antibiotic meta phylactic treatments against seasonal infectious bronchitis and viruses (de Mesquita Souza Saraiva et al., 2022). Antibiotic usage continues to be the most cost-effective measure while guaranteeing welfare principles and intervention effectiveness (Nanda et al., 2022). In broiler rearing systems, antibiotic drugs [aminoglycosides (streptomycin) (Mak et al., 2022), sulfonamides (sulfamethoxazole) (Divala et al., 2022), quinolones (enrofloxacin, marbofloxacin) (Haeili et al., 2022), and tetracycline (oxytetracycline and doxycycline) (Duga, 2018)] are approved by the EU and USA (Mader et al., 2022) and are included in the farm health protocol management. Moreover, antibiotic utilization in chickens is strictly regulated, for a therapeutic and preemptive purpose only (Mader et al., 2022), and slaughtering is permitted only after the antibiotic withdrawal period. Current data points out the antibiotic residue in meat and other poultry products (Ramatla et al., 2017; Oyedeji et al., 2019; Verma et al., 2020; Mak et al., 2022; Mohammadzadeh et al., 2022; Fei et al., 2023). The widespread curative and preemptive usage of antibiotics (quinolone, aminoglycosides, tetracyclines, and sulfonamides) for both humans and livestock, as sole active bacteriostatic agents, are contributing to the antimicrobial resistance phenomenon, with implications on the environment and human health (Gržinić et al., 2023). Nowadays, antibiotic resistance infections are more prevalent and often associated with high morbidity (Srisuwananukorn et al., 2021) and mortality (1.27 million cases globally) (Murray et al., 2022) among both adults and infants (de Kraker et al., 2016; Malik et al., 2019; Murray et al., 2022).

The current paper aims to increase public awareness and provide valuable supporting information for future policies to meat producers and consumers about the effects of antibiotic administration practices leading to accelerated extensive antibiotic resistance, thus contributing to the vast and contra-balanced health risks associated with infections.

The main objective was to evaluate the chicken-meat antibiotic residue content, group-specific antibiotic residue content, and consumers' antibiotic exposure (antibiotic-estimated daily intake) and hazard quotient.

2. Materials and methods

2.1. Chicken meat sampling

Chicken meat was sampled from March to April 2022 and July to September 2022, in twelve different areas (Figure 1) of Romania ($n = 6$ cities, and their rural surroundings), collecting a total of 348 chicken breast meat samples (Figure 2), from different provenances: 12% ($n = 42$) from commercial center origin, such as retail markets (RM, based on conventional intensive farming systems, sold in hypermarkets and supermarkets), 53% ($n = 185$) from traditional markets and local fairs (TM, individual producers or small-sized farms semi-intensive rearing systems), and 35% ($n = 121$) from door-to-door vendors via the internet market origin [DTD, exclusively extensive production systems (individual agricultural holdings, authorized as family farms, merchandising via the internet]. The collected breast meat samples were individually weighed ($1 \pm 0{,}120$kg/sample), with a technical balance (Axis AZT 320, Poland), and evaluated for water content (SR ISO 1442:2010). The organoleptic evaluation of the chicken meat samples (ISO 5492:2008) was conducted, with nine naïve assessors (ISO 8586:2023), mixed-sexes, aged between 23 ± 2 years

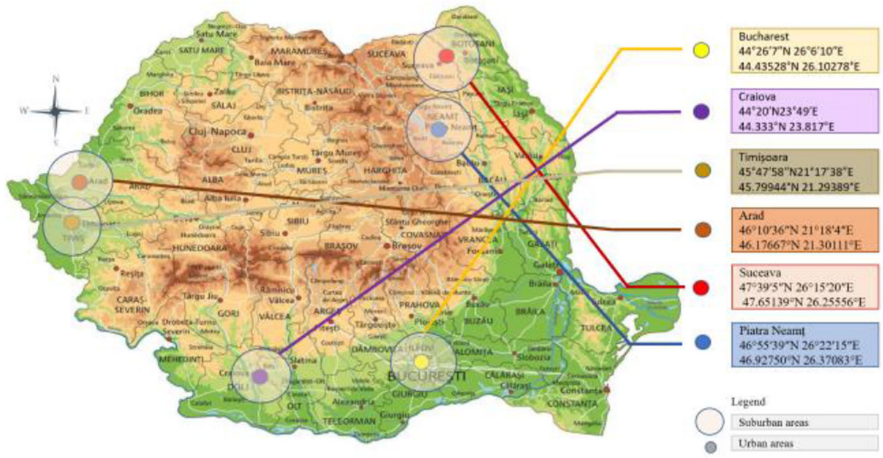

FIGURE 1
Chicken meat sampling places.

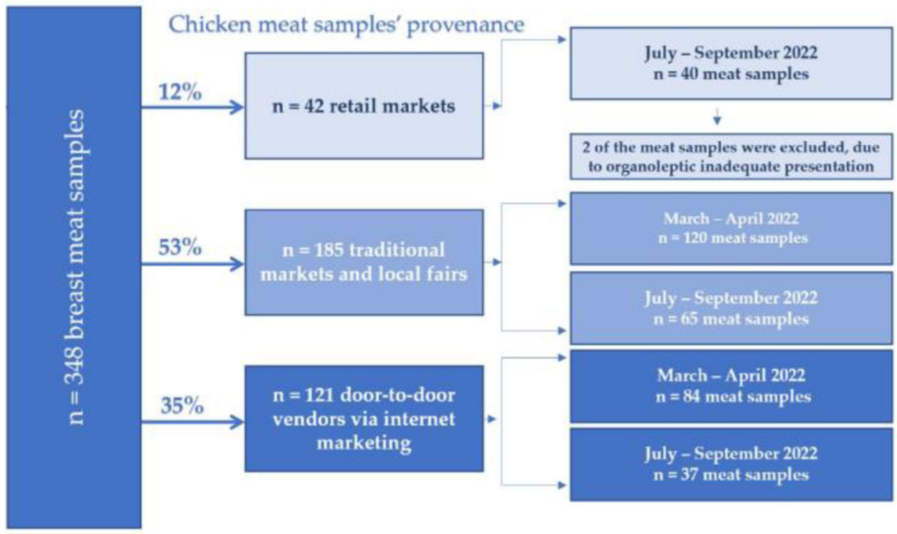

FIGURE 2
Chicken meat sampling protocol.

old, evaluated for the traded raw meat organoleptic standardized characteristics: carcass appearance, meat aroma, meat odor, meat consistency, and meat juiciness (EC 543/2008). There is a 1–5 hedonic scale response as for consumers purchasing choice (1 – unpleasant, 2 – satisfactorily, 3 – neither pleasant nor unpleasant, 4 – pleasant, 5 – very pleasant).

2.2. Meat antibiotic residue qualitative assessment

The qualitative screening methodology (de Kraker et al., 2016) employed the detection of antibiotic and sulfamide residues through their direct inhibitory action against *Geobacillus stearothermophilus* (GS). GS is an important bioindicator for the presence of antibiotics in meat and milk samples. The analysis protocol was previously developed by Liofilchem (2011), focusing on the meat antibiotic residues inhibition on the GS growth. The inoculation takes place with preincubation (30 min at 20°C) of the mixture meat extract-GS media. The quick germination and proliferation of the GS is expressed at the final step of incubation (at 64 ± 0.4°C, during 3.5h). Due to the sensitivity of *Geobacillus stearothermophilus* to antimicrobial agents, such as beta-lactams, tetracyclines, macrolides, lincosamides, aminoglycosides, sulphamides, aminoglycosides, sulphamides, sulfanilamides, benzyl pyrimidine, and quinolones, it is commonly used in veterinary medicine and with relevant MRL

(Maximum Residue Limits) ranges valid in Europe – regulation 37/2010 EC.

2.3. Chemicals, reagents, and apparatus

The purified water (18,2MΩ cm, Adrona SIA CB-2303, Latvia), meat antibiotic residue quick detection test (MeRA test, Liofilchem Diagnostici, Roseto, Italy), the analytic grade reagents such as methanol, acetonitrile, dimethyl sulfoxide (Merk KGaA, Darmstadt, Germany), and ammonium acetate, and the antibiotic standard reference enrofloxacin (ENR)marbofloxacin (MAR), streptomycin sulfate (STM), oxytetracycline (OTC), doxycycline (DOX), and sulfamethoxazole (SXT), were provided by the University of Agronomic Sciences and Veterinary Medicine for Bucharest, the Faculty of Animal Productions Engineering and Management, Food Industry Department.

2.4. Apparatus instrumental conditions and software

The HPLC-ELSD meat antibiotic residue analysis was performed using the Agilent 1260 Infinity II system. The Agilent 1260 Infinity II G7104C Flexible pump, Agilent 1260 Infinity II G7129 vial autosampler, and Agilent 1260 Infinity II G7116A multicolumn thermostat were employed. Compound separation was achieved using the ZORBAX Eclipse Plus C18 column 4.6 mm × 75 mm × 3.5 µ (Agilent, USA). For instrumental, and chemical analyte detection was employed the Agilent 1260 Infinity II ELSD G4260 detector, followed by quantification tool system Agilent Open Lab CDS for LC and LC/MS. The mobile phase had three components: ultrapure water, acetonitrile, and Tri fluoric acid; 900: 99: 1, v/v/v. The flow rate was 200 $\mu l/min^{-1}$, the sample injection volume was 2 µl, and the column temperature was 28°C. The auxiliary equipment was represented by a pH meter (WTW Multi 310, Germany), with an electrode (SenTix 41, WTW, Germany, stored in KCl 3M), a laboratory centrifuge (Boeco C28-A, Germany), vortex-mixer (Vortex Genie 2 mixer, USA), ultrasonic bath (Elmasonic S 50 R, Germany), and a rotary evaporator (Heidolph Rotary Evaporator Laborota 4000, Germany).

2.5. Meat sample chromatography preparation

The organoleptic quality appropriate meat samples were individually minced (using a conventional blender (Bosch, Hausgeräte GmbH, Germany) and weighed (10 ± 0.02 g) using an analytical balance (Kern ABJ 220–4M, Kerk & Sohn GmbH, Germany). An individual aliquot of each chicken meat sample was weighed (1 g), mixed with 2 g of anhydrous sodium sulfate, and saturated with 500 µl of acetonitrile. A repetitive double-cycle extraction in 25 ml acetonitrile was developed by ultrasonication for 20 min. The meat sample supernatants were collected in conical 50 ml Eppendorf tubes after the centrifugation (3000 rpm, 5 min) and frozen (−20°C) for lipid content removal. The meat sample products were filtered (0.45 nm, unsterile syringe filters) and finally concentrated by evaporation to 1 ml (45 °C, 200 mmHg, 80 rpm), and stored at −12°C, over 24 h, for further HPLC analysis.

2.6. Meat antibiotic quality assurance and quantitative assessment

Standard reference substances as powder or crystals [enrofloxacin (ENR, Fluka, China), marbofloxacin (MAR, Sigma Aldrich, Merk, Switzer-land), streptomycin sulfate (STR, Sigma Aldrich, Merk, Switzerland), oxytetracycline (OTC, European Pharmacopeia reference standard, Europe Council), doxycycline (DOX, Sigma Aldrich, Switzerland), and sulfamethoxazole (SMX, Merk, Italy)] were individually soluted as per producers' requirements, using the ultrasonication bath (15 min), reaching a final concentration of ∼1 mg/ml. The quality assurance for the analytical procedure was developed for accuracy, precision, sensitivity limit of detection and of quantification, working range, selectivity and specificity, presence of antibiotic recovery, ruggedness and robustness, and possible interferences. A calibration curve was developed, for each antibiotic analyte, spiked in 0, 5, 10, 50, 100, 250, and 500 µg/ml, taking into consideration the maximum antibiotic residue limits (FAO, 2015). For the simultaneous antibiotic residue determination, an aliquot (100 µl) of each stock solution was diluted to a total volume of 900 µl (600 µl analytes mixture + 400 µl mobile phase).

2.7. Health risk assessment

The consumer's antibiotic exposure was assessed for each of the four classes of antibiotics: quinolones, aminoglycosides, tetracyclines, and sulfonamides. The daily intake of antibiotics was estimated based on the individual antibiotic concentration and the chicken breast meat average daily consumption (27.8 kg/capita/year) (FAO., 2020). The daily antibiotic dose ingested through chicken breast meat was calculated, with the formula [1].

$$EDI = \frac{ACR\ (ug/kg) * MDI\ (kg/pers)}{ABW\ (kg)} \tag{1}$$

EDI, Estimated antibiotic residues daily intake; ACR, the antibiotic residue concentration, in this study (µg/kg fresh meat); MDI, the mean of meat daily intake, expressed as kg/person; ABW, The adult consumer average body weight reference, 70 kg (Aggarwal et al., 2022).

After calculating the EDI, the hazard quotient was estimated using the calculation formula [2].

$$HQ = \frac{EDI}{ADI} \tag{2}$$

HQ, hazard quotient; EDI, Estimated antibiotic residue daily intake; ADI, Acceptable antibiotic residue daily intake (Medicines V., 2002; Assessment and Mebendazole, 2010; EMEA., 2015; FAO, 2015; Bahmani et al., 2020; Kyriakides et al., 2020); interpretation: if HQ $<$ 1.0 – Acceptable, receptors are not exposed to the contaminant, if not (HQ > 1.0) – Not acceptable, the receptors are exposed to the contaminant.

2.8. Data processing and statistics

Agilent Open Lab CDS LC&LC/MS software (Agilent Technology Inc. USA) was used for processing and data acquisition, and the SPSS (version 25, IBM, USA) software was used for descriptive statistics and the Pearson correlation. The dimensionally reduction method of principal component analysis (PCA) was employed using the two components, F1 and F2, to explain all linear combinations with large variations.

3. Results and discussions

3.1. Organoleptic meat properties

At the start of the experiment (during the sampling procedure), all chicken breast meat samples ($n = 348$) were evaluated for organoleptic characteristics. Evaluating the organoleptic attributes of the broiler carcass and breast meat of TM and DTD groups did not indicate significant differences, except for two broiler carcasses belonging to the RM group. The two altered chicken carcasses also presented an unacceptable level of water addition, so the meat samples were excluded from the study, with the motivation of the meat quality being unfit for human consumption. The organoleptic characteristics of the chicken raw meat refer to the conditions that domestically produced poultry meat must meet to be marketed (Comunit C., 2008). Poorly and improperly processed meat has the potential to carry a zoonotic disease (Georganas et al., 2022), thus causing pathogenic contamination (French, 2023), and posing the highest risk for both human and animal health (Amore et al., 2022).

3.2. Meat antibiotic residue qualitative assessment

None of the 40 samples collected and analyzed originating from the retail market were confirmed positive for any category of antibiotics (Figure 3). Only nine chicken breast meat samples suspected of antibiotic residue presence were identified (false positive results) and kept for further quantitative antibiotic residue assessment. The results concerning the chicken breast meat samples from the TM group (during all experimental trials) presented an overall 75% ($n = 137$) antibiotic residue presence. Meanwhile, the total breast meat chicken collected from the DTD group ($n = 22$) showed a much higher antibiotic residue presence (82% of the DTD meat samples were positive for antibiotic residues). A potential explanation for the difference in antibiotic presence in the chicken breast meat samples' origin could be attributed to the antibiotic administration without respecting the drug withdrawal periods (Györke et al., 2013; Verma et al., 2020) and rushing the slaughtering protocols without considering the potential harmful effects. Generally, in extensive and intensive rearing management, the antibiotics have specific prophylaxis procedures, regarded as health-related mandatory actions, which are more focused on prevention and less therapeutic intervention, and strictly impose the drug withdrawal period before slaughtering (Mohammadzadeh et al., 2022), promoting product biosecurity and consumer safe.

3.3. Meat antibiotic quantitative assessment

The data presented in Table 1 highlight the most antibiotic-contaminated chicken breast meat was in the TM and DTD groups, and the antibiotic residues belonged to the quinolone antibiotics group, recommended for veterinary use and administered with restriction (EMA., 2019). Enrofloxacin was detected in 84% of

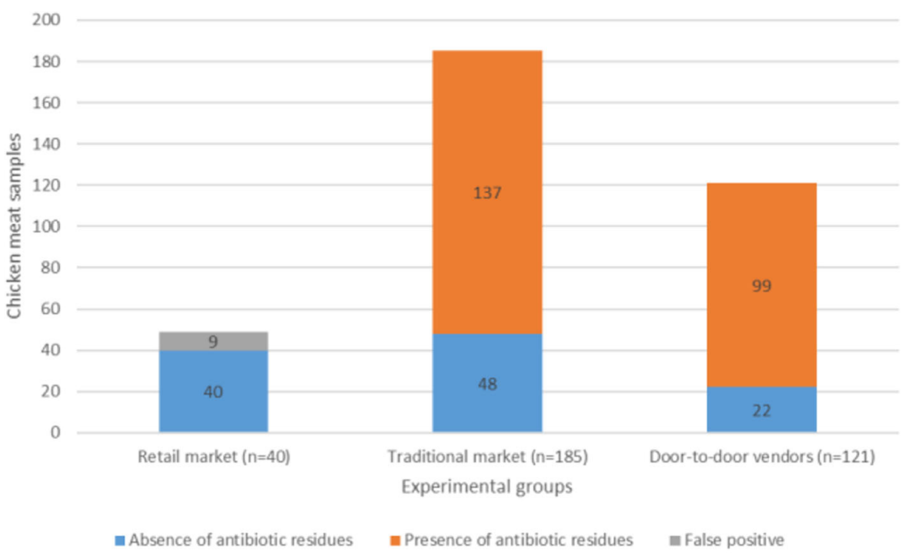

FIGURE 3
Presence of antibiotic residues in chicken breast meat samples.

TABLE 1 Chicken meat samples antibiotic residues mean concentrations (μg/kg).

Antibiotic abbreviation	μg/kg	Retail market origin chicken meat samples $n = 40$	Traditional market and local fairs chicken meat samples $n = 185$		Individual producers selling chicken meat door-to-door via internet marketing $n = 121$	
		March–September 2022 $n = 40$	March–April 2022 $n = 120$	July–September 2022 $n = 65$	March–April 2022 $n = 84$	July–September 2022 $n = 37$
ENR	% positive samples X ± Sx Min–Max	ND - -	84 7.41 ± 7.02 2.02–12.80	64 6.00 ± 6.40 0.85–11.15	75 10.00 ± 7.4 5.65–14.35	12 8.50 ± 3.14 6.46–10.54
MBX	% positive samples X ± Sx Min–Max	ND - -	18 52.00 ± 3.75 49.11–54.89	12 25.40 ± 2.14 20.00–30.80	43 32.00 ± 4.25 24.00–40.00	6 2.15 ± 0.85 1.40–2.90
STR	% positive samples X ± Sx Min–Max	ND - -	68 152.00 ± 3.75 120.00–184.01	19 127.50 ± 6.85 62.55–192.45	42 116.77 ± 6.65 77.8–155.69	20 70.50 ± 0.20 68.90–72.12
OTC	% positive samples X ± Sx Min–Max	ND - -	25 5.93 ± 2.24 4.75–7.12	19 3.15 ± 1.67 2.10–4.20	42 9.83 ± 5.35 8.45–11.20	23 6.93 ± 4.20 5.85–8.02
DOX	% positive samples X ± Sx Min–Max	ND - -	7 10.56 ± 3.44 8.95–12.18	3 10.98 ± 1.67 6.80–15.16	11 13.47 ± 1.60 12.15–14.80	8 11.78 ± 1.20 10.64–12.92
SMX	% positive samples X ± Sx Min–Max	ND - -	75 6.84 ± 2.02 5.80–7.88	22 4.31 ± 1.67 3.18–5.44	82 12.67 ± 6.65 7.15–18.20	34 7.80 ± 4.20 6.48–9.12

ENR, enrofloxacin; MBX, marbofloxacin; STR, streptomycin; OTC, oxytetracycline; DOX, doxycycline; SMX, sulfamethoxazole; X, mean value obtained; Sx, standard deviation value obtained; Min, minimum value obtained; Max, maximum value obtained; ND, antibiotic residue was not detected in the chicken meat samples.

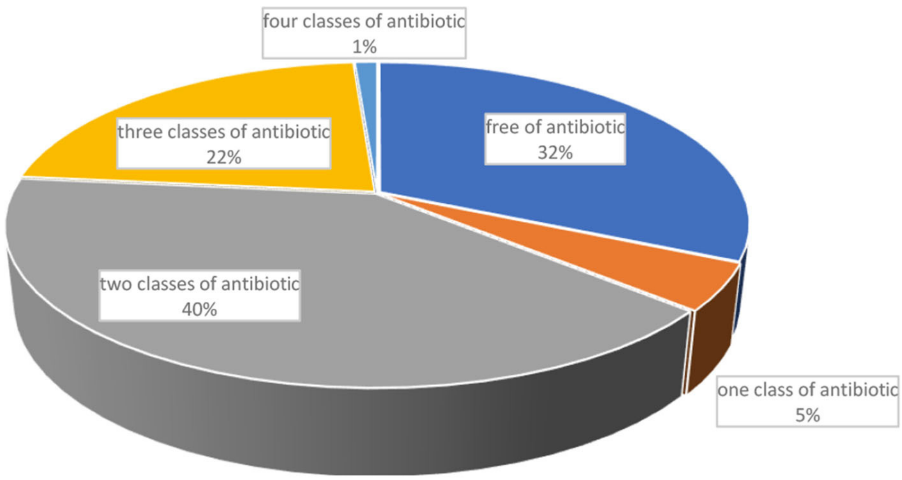

FIGURE 4
Group-specific antibiotic contamination in chicken breast meat samples.

samples from traditional markets and local fairs, in the first part of the year, with a maximum concentration of 12.80 μg/kg and a minimum concentration of 2.02 μg/kg. During the summer, the reported enrofloxacin residues in TM-origin broiler meat were higher (65% of total TM broiler meat samples) when compared with the DTD provenance meat samples (12%). Furthermore, in the spring season the enrofloxacin antibiotic residue present in the meat samples was higher, showing an 84% presence in the TM meat samples group when compared with the DTD meat samples group (75%). Current results point out the fact that among individual producers (DTD group), both the frequency of quinolone contamination and the maximum residue concentration of enrofloxacin is significantly lower when compared with the TM group. Regarding the variation of enrofloxacin concentration according to the months of the year, increased residue concentrations are found in chicken breasts sold in traditional markets and door-to-door in the colder months of the year, which also correspond to high atmospheric humidity when compared to the summer months. Similar situations have been reported internationally by other researchers (Panzenhagen et al., 2016; Moghadam et al., 2018; Kang et al., 2021; Foreign et al., 2022). Tetracycline residues were mainly detected in the spring months of the year, while oxytetracycline residues were detected in 42% of the total DTD-origin chicken breast meat samples during the spring season in 2022. The highest concentration of oxytetracycline was 11.20 µg/kg (spring season) and 8.02 µg/kg (summer season), with an average concentration of 9.83 µg/kg chicken breast from the DTD group in the spring and 6.93 µg/kg in the summer months. Similar results to our findings were previously reported by Salama et al. (2011) and Bahmani et al. (2020). Moreover, cross-contamination has been reported (Figure 4), indicating a multi-drug therapeutic intervention, although most of the antibiotics such as tetracyclines and aminoglycosides (Li, 2022) share the same group of targeted pathogens, so no justification could be attributed, and thus antibiotics are still used for the growth promotive effects. However, in this study, the largest group of antibiotic contaminants was sulfonamides (SMX). During the spring months, almost 82% of the total meat samples of the DTD group presented SMX contamination (7.15–18.20 µg/kg), followed by the TM-origin chicken breast meat samples (5.80–7.88 µg/kg) in the same seasonal conditions. SMX is a synthetically developed substance with broad bacteriostatic action against susceptible bacteria, interfering directly in their folic acid synthesis. In the current study, the maximum concentrations of antibiotic residues detected (ENR, MBX, STR, OTC, DOX, and SMX) in the broiler breast meat samples (Table 1) for TM and DTD in spring and summer conditions did not exceed the regimented limits (Europene CU., 2006).

3.4. Health risk assessment

The antibiotic residue contaminant exposure of the population was assessed for each of the four classes of antibiotics: quinolones, aminoglycosides, tetracyclines, and sulfonamides. The daily intake of antibiotics was calculated based on the concentration of antibiotics in the chicken meat consumed, and the daily consumption of chicken breast (27.8 kg/capita/year). The current results were compared with the MRL values (Table 2), and no analyzed chicken breast meat sample exceeded the MRL values, indicating the meat is safe and suitable for human consumption. The estimated maximum daily intake (Table 3) for the antibiotic analytes ranged from 2.932 ng/kg-bw (body weight)/day of MBX in summer to 194.544 ng/kg-bw/day of STR for adults during the summer period. However, chicken meat is often recommended for consumption to children of all ages, starting at 6 months of age, although safe limits

TABLE 2 Maximum residue limits of antibiotics (Salama et al., 2011).

Antibiotic classes	Quinolones		Aminoglycosides	Tetracycline		Sulphonamides
Targgeted group	Group B		Group C	Group D		
Veterinary administration required	Under restriction administration		With precaution administration	With caution administration		
Antibiotic active substance (abbreviation)	Enrofloxacin (ENR)	Marbofloxacin (MBX)	Streptomycin (STR)	Oxytetracycline (OTC)	Doxycycline (DOX)	Sulfamethoxazole (SMX)
Antibiotic MRL	100 µg/kg		600 µg/kg	200 µg/kg		100 µg/kg

ENR, enrofloxacin; MBX, marbofloxacin; STR, streptomycin; OTC, oxytetracycline; DOX, doxycycline; SMX, sulfamethoxazole; MRL, maximum residue limits.

TABLE 3 Consumers' health risk assessment (µg/kg).

Antibiotics	Traditional market and local fairs merchandised chicken meat				Door-to-door via the internet sold chicken meat			
	March–April 2022		July–September 2022		March–April 2022		July–September 2022	
	EDI*	HQ	EDI	HQ	EDI	HQ	EDI	HQ
ENR	0.012939	0.00647	0.011271	0.005636	0.014506	0.007253	0.010655	0.005327
MBX	0.055487	0.01734	0.031135	0.00973	0.040435	0.012636	0.002932	0.000916
STR	0.186012	0.00744	0.194544	0.007782	0.157384	0.006295	0.072905	0.002916
OTC	0.007197	0.000288	0.004246	0.00017	0.011322	0.000453	0.008107	0.000324
DOX	0.012313	0.004104	0.015325	0.005108	0.014961	0.004987	0.013061	0.004354
SMX	0.007966	0.000637	0.005499	0.00044	0.018398	0.001472	0.009219	0.000738

*EDI was expressed as µg/kg body weight/day, HQ, hazard quotient; ENR, enrofloxacin; MBX, marbofloxacin; STR, streptomycin; OTC, oxytetracycline; DOX, doxycycline; SMX, sulfamethoxazole.

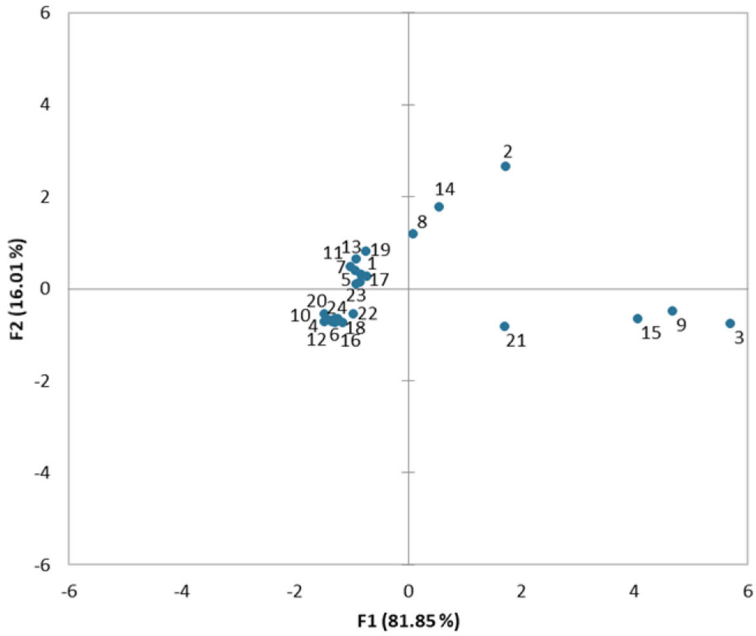

FIGURE 5
Principal component analysis plot. Traditional market trade meat: 1, Enrofloxacin residues encountered during spring; 2, Marbofloxacin residues encountered during spring; 3, Streptomycin residues encountered during spring; 4, Oxytetracycline residues encountered during spring; 5, Doxycycline residues encountered during spring; 6, Sulfamethoxazole residues encountered during spring; 7, Enrofloxacin residues encountered during summer; 8, Marbofloxacin residues encountered during summer; 9, Streptomycin residues encountered during summer; 10, Oxytetracycline residues encountered during summer; 11, Doxycycline residues encountered during summer; 12, Sulfamethoxazole residues encountered during summer. Door-to-door via Internet traded meat: 13, Enrofloxacin residues encountered during spring; 14, Marbofloxacin residues encountered during spring; 15, Streptomycin residues encountered during spring; 16, Oxytetracycline residues encountered during spring; 17, Doxycycline residues encountered during spring; 18, Sulfamethoxazole residues encountered during spring; 19, Enrofloxacin residues encountered during summer; 20, Marbofloxacin residues encountered during summer; 21, Streptomycin residues encountered during summer; 22, Oxytetracycline residues encountered during summer; 23, Doxycycline residues encountered during summer; 24, Sulfamethoxazole residues encountered during summer.

for antibiotic residues in foods consumed by children are not currently available. This might represent a considerable risk due to children's immune system issues and gastric imbalances. An avoidance strategy might be represented by approaching a diet with a diverse range of protein sources that meets the daily nutritional requirements for children. The hazard index had a subunit value (Table 3) in adults, which is why we can say that the detected levels of antibiotic residues in the chicken breast could not be considered a public health threat regarding these veterinary antimicrobial substances presence (Oyedeji et al., 2019). Recent studies in China (Fei et al., 2023) and Greece (Stavroulaki et al., 2022) present similar results concerning consumer safety and chicken meat antibiotic contaminants exposure.

3.5. Correlations

The total variance (97.86%) is explained by the PCA analysis plot (Figure 5) (F1= 16.01% and F2 = 81.85%). Strong correlations were obtained between the meat antibiotic residues among the studied trade systems and seasonal differences. The residues of ENR – DOX (groups 1, 5, 7, 11, 13, 17, and 19) and OTC - SMX (groups 4, 6, 10, 12, 16, 18, 20, and 22) were clustered and might represent a cause of similar antibiotic administration among both commercial groups in both seasons. The STR antibiotic residue meat presence plotted dispersion appears different from all other antibiotic residues (Verma et al., 2020; Pandey and Kumar, 2021; Barbut and Leishman, 2022; Haeili et al., 2022), suggesting their targeted administration strategy among the studied antibiotic residue groups have low levels on the studied meat traded samples. The analysis processing data showed the correspondence among the antibiotic residue's meat samples origin (trade market and door-to-door traded meat antibiotic residues variations) and the seasonal variations (Table 4). The first dimension (F1) explains 81.85% and the second one (F2) 16.10% of the total inertia.

4. Conclusions

Chicken meat antibiotic residues are a current global challenge and present severe consequences concerning consumer health safety. In our study, the chicken meat from traditional markets and local fairs and individual producers selling via the internet contained more antibiotic residues when compared with the meat from retail markets, most probably because individual

TABLE 4 Contributions and squired cosines of the experiments.

Item	Contributions (%)		Squired cosines	
	PC1	PC2	PC1	PC2
1	0.8378	2.2077	0.6386	0.3293
2	3.0223	36.4382	0.2936	0.6925
3	33.0327	3.0084	0.9722	0.0173
4	1.8277	2.7618	0.7717	0.2282
5	0.8423	0.0404	0.9902	0.0093
6	1.6658	2.2572	0.7900	0.2095
7	1.0578	1.1866	0.7941	0.1743
8	0.0083	7.4648	0.0057	0.9943
9	22.2505	1.2833	0.9366	0.0106
10	2.2062	2.7340	0.8048	0.1951
11	0.6979	0.4866	0.8706	0.1188
12	2.0072	2.3794	0.8117	0.1883
13	0.5684	3.3627	0.4567	0.5286
14	0.3199	16.5024	0.0901	0.9091
15	16.7658	2.2347	0.9732	0.0254
16	1.3582	2.8009	0.7111	0.2870
17	0.5397	0.3468	0.8827	0.1110
18	0.9389	1.5333	0.7533	0.2407
19	0.8817	0.7821	0.8509	0.1477
20	2.2128	1.5377	0.8802	0.1197
21	2.9961	3.6024	0.6813	0.1603
22	1.7021	2.7801	0.7574	0.2420
23	0.7206	0.0920	0.9717	0.0243
24	1.5394	2.1765	0.7829	0.2166

PC1, Principal component 1 combination of variables; PC2, Principal component 2 combination of variables. TM samples codification: 1, Enrofloxacin residues encountered during spring; 2, Marbofloxacin residues encountered during spring; 3, Streptomycin residues encountered during spring; 4, Oxytetracycline residues encountered during spring; 5, Doxycycline residues encountered during spring; 6, Sulfamethoxazole residues encountered during spring; 7, Enrofloxacin residues encountered during summer; 8, Marbofloxacin residues encountered during summer; 9, Streptomycin residues encountered during summer; 10, Oxytetracycline residues encountered during summer; 11, Doxycycline residues encountered during summer; 12, Sulfamethoxazole residues encountered during summer. DTD samples codification: 13, Enrofloxacin residues encountered during spring; 14, Marbofloxacin residues encountered during spring; 15, Streptomycin residues encountered during spring; 16, Oxytetracycline residues encountered during spring; 17, Doxycycline residues encountered during spring; 18, Sulfamethoxazole residues encountered during spring; 19, Enrofloxacin residues encountered during summer; 20, Marbofloxacin residues encountered during summer; 21, Streptomycin residues encountered during summer; 22, Oxytetracycline residues encountered during summer; 23, Doxycycline residues encountered during summer; 24, Sulfamethoxazole residues encountered during summer.

farmers' antibiotic resistance awareness is still quite low. Generally, more than 40% of total analyzed chicken meat samples were positive for two classes of antibiotics, most of them belonging to the traditional markets and local fairs merchandised group. The higher antibiotic contamination rate in samples taken from small-size farms and individual farmers suggest a need for a more rigorous control of drugs and antibiotics. Moreover, our results proved that local individual and small-size farming has increased the need for knowledge and education about antibiotic drugs used to ensure prudent approaches toward preventing health hazards and ensuring durable and sustainable meat products. There is a lack of information and national and local level protocols and campaigns about proper antibiotic management and respecting the withdrawal periods concerning consumer safety.

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 authors.

Author contributions

EP: conceptualization, methodology, and investigation. D-MG: writing—original draft, investigation, and software. DI, DP, and GB: investigation. DP and IP: validation. IP, ND, and D-MG: conceptualization, writing—review and editing, and supervision. All authors contributed to the article and approved the submitted version.

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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

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nLCA in bakery food products: state of the art and urgent needs

Martina Cassarino[1]*, Gianluca Giuberti[1], Lorenzo Morelli[1], Marco Trezzi[2], Andrea Pelattieri[2], Loris Manicardi[3] and Pietro Scaglia[3]

[1]Department of Sustainable Food Process – DiSTAS, Università Cattolica del Sacro Cuore, Piacenza, Italy, [2]Research and Development Department, Bauli S.p.A., Verona, Italy, [3]Deloitte & Touche S.p.A., Milan, Italy

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EDITED BY
Rakesh Bhardwaj,
Indian Council of Agricultural Research (ICAR), India

REVIEWED BY
Natasha R. Marak,
Central Agricultural University, India
Shalini Gaur Rudra,
Indian Agricultural Research Institute, India

*CORRESPONDENCE
Martina Cassarino
✉ martina.cassarino@unicatt.it

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This study analyzes the nutritional life cycle assessment (LCA) of bakery products and the current state of the art. The analysis focuses on (1) the importance of applying a methodology, such as LCA, in a general way and the division into different stages considering the UNI EN ISO; (2) the development of nutritional LCA; (3) the difference between functional units in LCA and nutritional LCA; and (4) the different nutritional LCA approaches. The study emphasizes the lack of nutritional LCA studies regarding the bakery category, underlining the urgent need for this type of investigation concerning this specific food sector.

KEYWORDS

life cycle assessment, nutritional life cycle assessment, bakery, cereals, sustainability

1 Introduction

The food system contributes approximately one-third of the total anthropogenic greenhouse gas (GHG) emissions (Tubiello et al., 2021). The term "carbon" refers to greenhouse gases because carbon dioxide is the main greenhouse gas released by different human activities. The activity that is used for this measurement is referred to as "carbon footprinting." Product carbon footprinting also includes emissions over the entire life cycle of a product or service, from raw material extractions through production to use and reuse (Bouchery et al., 2017). This aspect, combined with the fact that the world population is expected to increase by 2050 (Ansari et al., 2011), will lead to more intensive agriculture to meet the growing demand for food and, consequently, the overuse of natural resources (Tilman et al., 2011). In parallel, consumers' interest in safe, high-quality products produced with the least environmental impact has progressively increased (De Boer, 2003).

The increased importance of environmental protection and the possible impacts associated with products have increased interest in developing methods to better understand and address these impacts (UNI EN ISO 14040, 2006). One of the techniques being developed for this purpose is life cycle assessment (LCA). Today, LCA is the most widely used approach to model and calculate the environmental impacts of certain products and processes. In addition, the LCA methodology is at the core of sustainability assessment and is used to evaluate the environmental impact associated with alternative agricultural and food technologies, food supply chains, ingredients, foods, meals, and whole diets (McLaren et al., 2021). The international normative reference for the execution of LCA studies is the 14040 series of ISO standards, particularly the UNI EN ISO 14040 (i.e., environmental management, life cycle assessment, principles, and framework) and the UNI EN ISO 14044 (i.e., life cycle assessment, requirements, and guidelines). LCA comprises four iterative phases: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase (Figure 1).

2 General view on the principles of the life cycle assessment

The scope of LCA, including the system boundary and level of detail, depends on the subject and intended use of the study (UNI EN ISO 14040, 2006). Establishing the intended application, such as product improvement, strategic planning, and policy-making for sustainability, is important. In addition, the functional unit (FU) is a critical aspect of the scope and quantitatively describes the function (Cucurachi et al., 2019). ISO 14040 and 14044 state that the specific FU should be chosen according to the objective and purpose of the study, and Schau and Fet (2008) stated that it is the unit to which the results of the LCA are reported. The FUs most commonly used in food LCAs have, until now, been based on mass or volume (McAuliffe et al., 2020).

The life cycle inventory analysis (LCIA) phase is the second phase of LCA. It involves collecting data, identifying relationships, and quantifying the inputs and outputs of the system (UNI EN ISO 14040, 2006). It is important at this stage to define the unitary processes that make up the system. In this way, the "elementary flows," are recorded, i.e., all natural resources extracted from the environment, and the "economic flows." The boundaries of the system are defined to help understand what to evaluate and what to omit, which should cover the entire life cycle from upstream to downstream of the system. Depending on the product in question, the boundaries of the system will change. However, processes rarely produce a single economic output, that is, when a product or system consists of multiple parts or processes (Cucurachi et al., 2019). In this situation, it is crucial to consider the allocation rules, i.e., rules that attribute the environmental impact of a product or system to its parts or activities. Another aspect to include is that the data are divided into those relating to inputs and those corresponding to output flows. The collected data can be divided into primary and secondary; the difference is that the primary data are those coming from direct surveys; the latter, on the other hand, are drawn from the literature. At the end of this phase, an inventory table will be constructed between the system being assessed and the natural environment (Cucurachi et al., 2019).

The life cycle impact assessment (LCIA) phase is the third phase of the LCA. The purpose is to use predefined methods in the LCA software to group and aggregate a system's LCI results to better understand their environmental significance (UNI EN ISO 14040, 2006). The results of the inventory analysis are multiplied by the respective global warming potentials (GWPs), and the greenhouse gas emissions (CO_2 and CH_4) are expressed in kg of CO_2 equivalent (Cucurachi et al., 2019). The impact assessment phase is divided into several elements: classification, characterization, and standardization. The classification consists of aggregating inventory data based on the type of environmental impact; characterization deals with calculating the relative contributions of emissions and resource consumption to each environmental impact; and in normalization, the results are dimensionless so that they can be compared with a reference value. Each LCA must include classification and characterization.

Life cycle interpretation is the final phase of the LCA procedure, in which the results of an LCI, LCIA, or both are summarized and discussed for conclusions, recommendations, and decision-making in accordance with the definition of the goal and scope (UNI EN ISO 14040, 2006). This phase highlights potential areas for improvement related to hotspots in the lifecycle.

There has been increased interest among nutrition and environmental scientists regarding nutritional quality and health impacts (Bianchi et al., 2020). Accordingly, Broekema and Blonk (2020) argued that, for a product to be future-proof, it is important that a good balance exists between nutrition and environmental impact. Consequently, when evaluating agri-food products, researchers have considered incorporating nutritional science into environmental LCA studies. This analysis has become known as

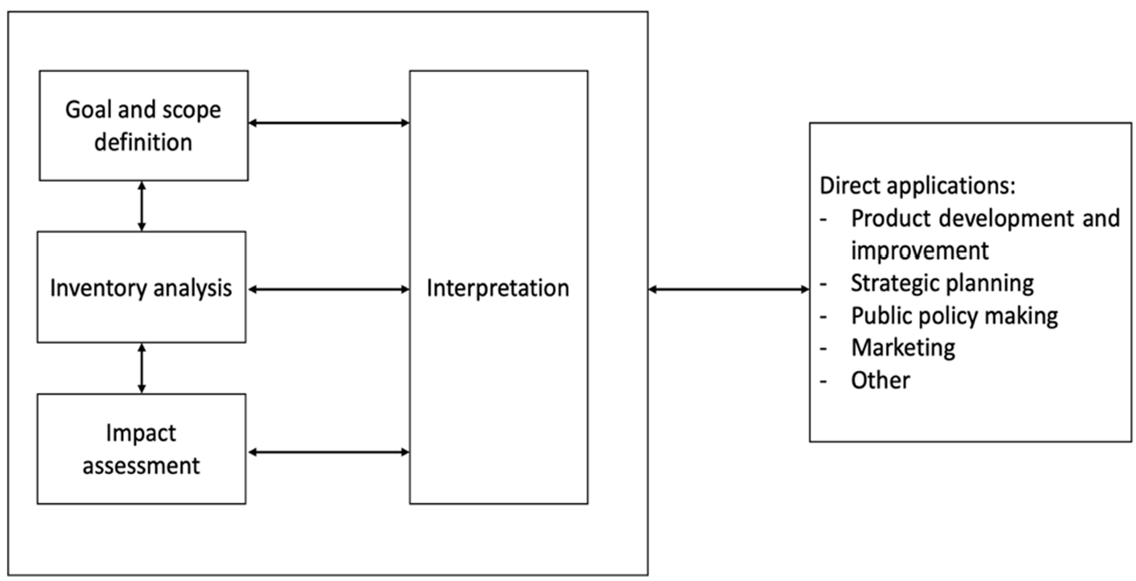

FIGURE 1
Different stages of LCA (UNI EN ISO 14040, 2006).

nutritional LCA (nLCA) (McAuliffe et al., 2020; McLaren et al., 2021). In short, the nLCA addresses the food–nutrition–environment nexus. The nLCA considers the nutritional impact of the product by assessing its nutritional quality, processing methods, and its nutritional value. In the FAO document, McLaren et al. (2021) used this term to refer to an LCA in which nutrient supply is considered the main functional unit (FU). Moreover, nLCA studies can help identify the healthiest and most environmentally friendly options for consumers. In this context, McAuliffe et al. (2023) pointed out that the use of simplified nutritional FUs (nFUs) is one of the main problems in LCA. Currently, nFUs are used to provide a common unit of analysis to standardize the comparative LCA of alternative food products.

In addition, it is important to distinguish the role that nutrition can play in the functional unit and in the calculation of impacts (Weidema and Stylianou, 2019). Knowing that the nutrient content in nLCA is considered critical, one cannot exclude some nutrients rather than others. According to Weidema and Stylianou (2019), the degree of satiety of food should also be considered, as it indicates the time that passes until the next meal is requested. For a given food product, the inclusion of the nutrient content along with the satiety in the nLCA can therefore be used as a functional unit. However, it is important to consider the other side of the coin: Could nutrition also have an impact on human health? It is necessary to consider a framework that, in terms of nLCA, combines foods and diets with harms and benefits for human health. In particular, Weidema and Stylianou (2019) have proposed an index, the Daly Nutrition Index (DANI), which provides continuous single-score quantification, expressed in disability-adjusted life years (DALYs) per functional unit of food, of associated marginal (small, additional) health burden from all-cause premature mortality and disease morbidity and uses Global Burden of Disease (GBD) epidemiological evidence to classify and evaluate foods and diets. This index can be used as a nutritional health assessment method aligned with LCA, and it can be combined with the nutrient balance indicator to improve differentiation at the level of individual nutrients. However, although DANI places a focus on food groups and dietary patterns, it may not give correct indications of the level of diets.

3 Application of life cycle assessment methodology

LCA methodology has been widely applied to industrial products and processes, with special emphasis on the food system and related products. In particular, the environmental impacts of conventional and alternative production systems are described by this methodology, which identifies opportunities to develop sustainable production systems with minimal environmental impact (Green et al., 2006). Concerning the bakery product food sector, Roy et al. (2009) combined the organic production of wheat, industrial milling, and a large bread factory, considering it the most advantageous method for bread production. Noya et al. (2018)evaluated the environmental impact linked to the production of gluten-free biscuits in the UK following an LCA perspective and reported that ingredient production and transport activities are the main environmental hotspots in the examined impact category. Andersson and Ohlsson (1999) conducted an LCA case study of common white bread, aiming to compare different scales of production and potential environmental effects. In particular, the system included agricultural production, milling, baking, packaging, transport, consumption, and waste management. In addition, the authors considered different scales: a home bakery, a local bakery, and two small industrial bakeries with different distribution areas. In this case study, the four phases of the LCA ranged from the definition of the objective and scope, followed by the analysis of inventory analysis and impact assessment, whereas the final stage was the interpretation of the results. The authors concluded that the differences between home baking, the local bakery, and the small industrial bakery were not significant.

In the LCA, the FU is used as a reference unit and as the basis for any product comparison. McLaren et al. (2021) in the FAO report on the integration of environment and nutrition in food LCA, which contains recommendations on how to conduct a nutritional LCA, focus on the nUF that should be chosen. In this case, the nFU must be chosen based on the simultaneous consideration of environmental impact and nutritional/health aspects (McLaren et al., 2021). However, there is no established method for defining an nFU. As a result, different nFUs are used depending on the study. A protein nFU is used to include nutritional functionality in the LCA and is one of the most widely used FUs (Oonincx and de Boer, 2012; Saarinen et al., 2017). In addition, the studies in the literature are based on diet-level comparisons and consequently fail to guide farmers on how best to produce food (McAuliffe et al., 2020). Furthermore, nLCA can consider changes in diet within different populations (Sonesson et al., 2017, 2019). Batlle-Bayer et al. (2020) evaluated the environmental impacts of current average regional diets in Spain. They considered an FU based on both nutritional and socioeconomic dimensions. The authors noted that environmental benefits result from adopting a diet based on the National Dietary Guidelines (NDGs). In particular, NDGs are public documents that provide recommendations and advice on healthy diets and lifestyles. In addition, NDGs give guidance on individual foods that should be consumed to improve health and can provide quantitative recommendations by food groups or more general qualitative advice on overall diets. In the literature, the meal is considered an FU, representing the sum of the environmental impacts of each individual ingredient. In fact, Mazac et al. (2023) compared the environmental impacts of meals including novel/future foods with those of vegan and omnivore meals. The authors aimed to show that the use of nLCA has the advantage of considering nutrition as a FU in assessing food sustainability.

As mentioned above, nutrients should be considered in the development of an nLCA, and the most widely used method to supplement them is based on the use of nutritional indices, which, however, can include nutrients to be encouraged and limited. These indices, therefore, must be combined, even if their combination can produce negative values. For this reason, Saarinen et al. (2017) and McLaren et al. (2021) proposed to use an index based on the nutrients to be encouraged as FU and to assess the impact of the nutrients to be restricted. Should the index be used for all foodstuffs, or should a product-group-specific approach be taken? McLaren et al. (2021) and Scarborough et al. (2010) proposed to use a product-group-specific nutrition index in the UF, and Saarinen et al. (2017) introduced an index such as nFU, the Finnish Nutrient Index (FNIprot), for protein-rich foods. However, using different indices according to different product categories leads to different results for the study of LCA.

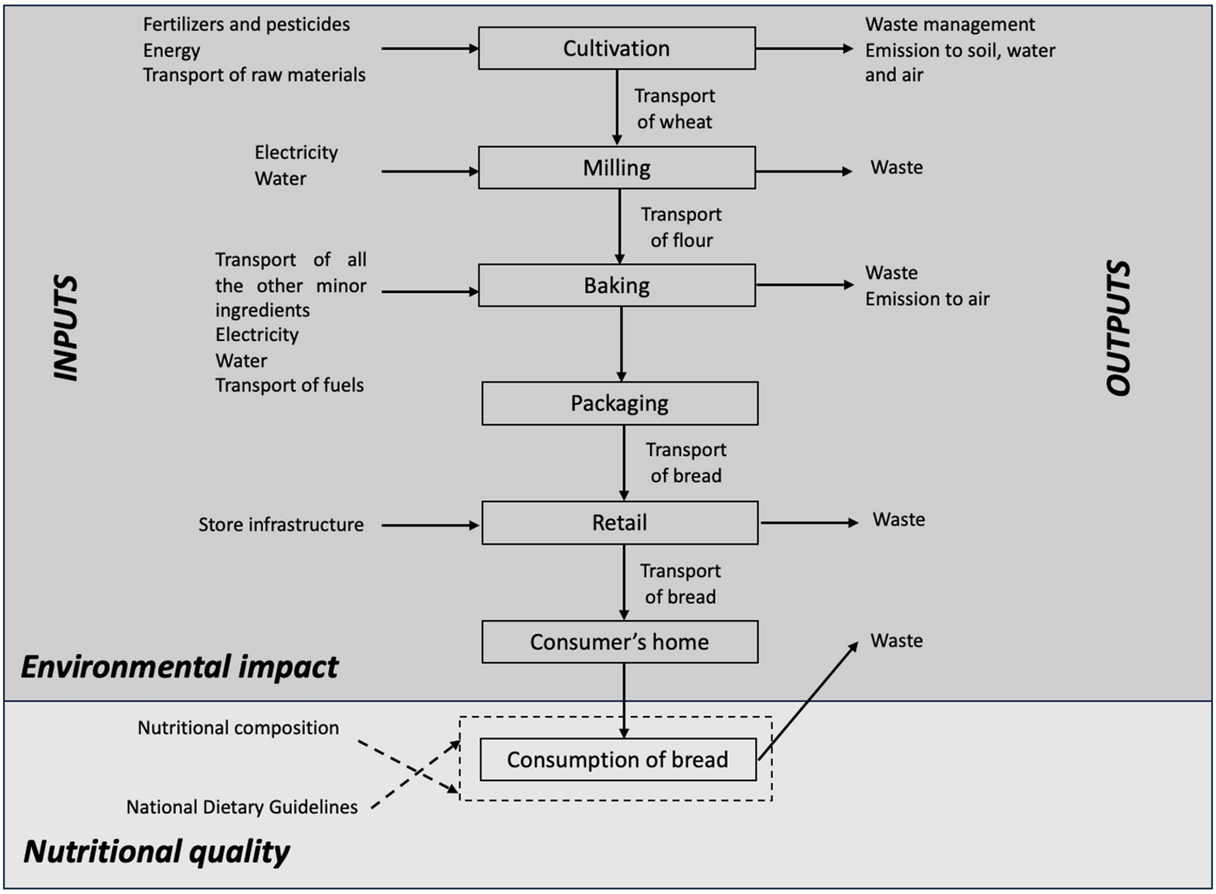

FIGURE 2
Illustrative flowchart considering the environmental impact combined with the nutritional quality of common white bread to provide possible guidance for conducting a nutritional LCA in this food system.

4 Urgent needs for cereal-based food products

Concerning food products, wheat flour, pasta, bread, and bakery products are widely consumed due to their convenience and affordability (Dinelli et al., 2009; Cappelli et al., 2018). For example, Green et al. (2006) underlined that bread is consumed in the UK by 96% of the population, whereas Nadi et al. (2022) stated that bread is featured in the diet of three-quarters of the world's population due to its nutritional and economic value. Accordingly, cereal-based food products are globally considered to be essential for human nutrition because they are an important source of macronutrients (i.e., mainly starch and protein), micronutrients, dietary fiber, and energy (Cappelli and Cini, 2021). In addition, bakery products may contain various bioactive compounds that can provide a series of different health-related benefits (Dinelli et al., 2009). However, as far as we know, no published studies have considered the nLCA of different cereal-based bakery food products. This may be concerning, as integrating nutritional aspects with environmental indicators is particularly important in the context of bakery food systems. Therefore, the goal is to develop a more comprehensive and integrative approach to suggest sustainability strategies for shaping future dietary patterns. In this context, referring to common industrial bread, and after the definition of the FU, one of the possible strategies to conduct an integrated approach should be a system in which the production of inputs to the cultivation of wheat, milling, all types of transportation, energy used, different baking processes, packaging, consumption, and waste management are considered. Of course, similar considerations should be applied not only for major ingredients entering a bread recipe but also for all the minor components, including, but not limited to, water, salt, and yeast. Obviously, all the components can change according to each specific cereal-based food product. Then, accounting for the fact that food serves a nutritional function as well as having direct environmental impacts, the obtained data from the LCA evaluation should be aggregated with the nutritional composition of bread and with the NDGs specific to this type of food product in an effort to provide an all-inclusive approach for current and future food systems (Figure 2).

To date, only a few studies have considered nLCA, but from a general point of view. There are studies in the literature that use nLCA to assess the impact of diet on the environment without considering individual food categories. For example, Batlle-Bayer et al. (2020) defined the FU of a diet as the annual basket of representative food items, divided into eight categories (vegetable base, meat, fish, eggs, dairy, ready meals, desserts, and beverages), consumed by a Spanish citizen that provides the required energy and nutrient intake. They

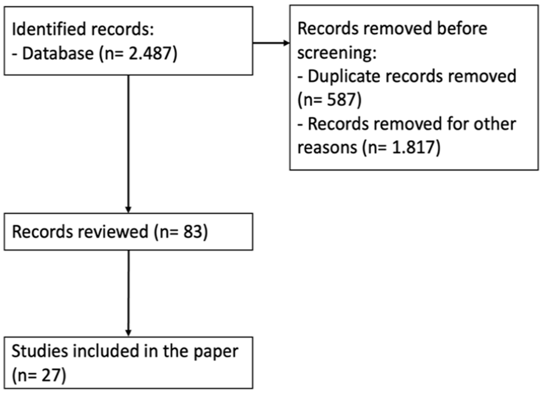

FIGURE 3
Bibliographic research flowchart.

assessed the environmental impacts associated with average regional diets in Spain and those of a diet based on the NDGs. The results showed that the NDG diet could reduce the environmental impact by between 15 and 60% by using this type of FU.

Other studies took protein as the FU of nLCA, considering it only a macronutrient. McAuliffe et al. (2023) stated that, although protein is considered an FU in the nLCA, it does not represent the nutritional value of a protein-rich food because it does not take into account the assessment of the macro- and micronutrients that compose it.

The bibliographic research was carried out on different datasets, and Figure 3 shows the method used to carry it out. It is important to know whether we consider the FU of the nLCA; the category of bakery products is further behind other categories, such as the milk category, in which different functional units have not yet been established and defined. Guerci et al. (2013) were the first to consider 1 kg of fat- and protein-corrected milk (FPCM) as a FU, which is based on fat content (4%) and protein (3.3% of true protein).

5 Future perspective and conclusion

This mini-review took a closer look at how the world of sustainability is gaining momentum. Consideration must be given to the environmental impact that a product and/or product category has on the environment, as the population is expected to increase by 2050. One of the methods used in the food world is LCA, which, based on UNI EN ISO 14040 and UNI EN ISO 14044, gives a general overview of how to approach this type of analysis, which differs from product to product. At the end of the entire process, LCA assesses the environmental footprint of the product and/or product category that has been analyzed. Recent research suggests considering both environmental and nutritional impacts, referring to the nLCA. Especially in the bakery world, this type of analysis is still in its infancy. Therefore, this is an important gap, mainly due to the lack of studies that take into account both the environmental and nutritional footprint. In this context, it is important to look to the future by expanding nLCA studies on bakery products.

Author contributions

MC: Writing – original draft. GG: Writing – review & editing. LMo: Writing – review & editing. MT: Writing – review & editing. AP: Writing – review & editing. LMa: Writing – review & editing. PS: Writing – review & editing.

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Conflict of interest

MT and AP were employed by Bauli S.p.A. LM and PS were employed by Deloitte & Touche S.p.A.

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EDITED BY
Graham A. McAuliffe,
Rothamsted Research, United Kingdom

REVIEWED BY
Judith Capper,
Harper Adams University, United Kingdom
Giuseppe Pulina,
University of Sassari, Italy
Gianni Battacone,
University of Sassari, Italy

*CORRESPONDENCE
Louise C. McNicol
✉ lsm20fqj@bangor.ac.uk

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

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The nutritional value of meat should be considered when comparing the carbon footprint of lambs produced on different finishing diets

Louise C. McNicol[1*†], Lynda S. Perkins[2†], James Gibbons[1], Nigel D. Scollan[2], Anne P. Nugent[2], Eleri M. Thomas[3], Elizabeth L. Swancott[3], Colin McRoberts[4], Alison White[4], Simon Chambers[4], Linda Farmer[4] and A. Prysor Williams[1]

[1]School of Environmental and Natural Sciences, College of Environmental Sciences and Engineering, Bangor University, Bangor, Gwynedd, Wales, United Kingdom, [2]Institute for Global Food Security, School of Biological Sciences, Queen's University Belfast, Belfast, Northern Ireland, United Kingdom, [3]Hybu Cig Cymru – Meat Promotion Wales, Tŷ Rheidol, Parc Merlin, Aberystwyth, Wales, United Kingdom, [4]Agri-Food and Biosciences Institute, Belfast, Northern Ireland, United Kingdom

Introduction: Lamb production systems are under increasing pressure to reduce their environmental footprint, particularly emissions of greenhouse gases (GHGs) such as methane. However, the metrics used to express the carbon footprint of lamb seldom consider its nutritional density and contribution to balanced diets in humans. Lamb production systems vary considerably, from low-input pastoral systems to higher-input systems feeding concentrates for the latter 'finishing' period. To date, no studies have explored the effect of finishing diet on the carbon footprint of lamb meat on a nutritional basis.

Methods: Data from 444 carcasses were collected from four abattoirs across Wales, United Kingdom. Lambs were derived from 33 farms with one of four distinct finishing diets: *forage crops* (n = 5), *grass* (n = 11), *concentrates* (n = 7), and *grass and concentrates* (n = 15). Carcass data were analysed using mixed effects models. Significant differences were found in fatty acid composition of two large commercial cuts of meat from different finishing diets. To illustrate the effect of different measures of footprint, mass (kg dwt) and omega-3 polyunsaturated fatty acid content (g omega-3) were selected as functional units. GHG emission estimates were calculated using Agrecalc.

Results: The *concentrates* diet had the lowest average mass-based product emissions [25.0 kg CO_2e/kg deadweight (dwt)] while the *grass* systems had the highest (28.1 kg CO_2e/kg dwt; p < 0.001). The *semimembranosus* muscle cut from the *forage crops* diet had the lowest average nutrition-based product emissions (19.2 kg CO_2e/g omega-3); whereas the same muscle cut from lambs finished on the grass and concentrates diet had the highest nutrition-based product emissions (29.4 kg CO_2e/g omega-3; p < 0.001).

Discussion: While mass-based functional units can be useful for comparing efficiencies of different farming systems, they do not reflect how farming systems impact the nutritional differences of the final product. This study demonstrates the importance of considering nutrition when expressing and comparing the carbon footprints of nutrient-dense foods such as lamb. This approach could also help inform discussions around the optimal diets for lamb production systems from both a human nutrition and environmental sustainability perspective.

KEYWORDS

sheep systems, farm management, fatty acids, human nutrition, environmental impacts of meat, Omega-3, nutritional LCA, sustainable agriculture

1 Introduction

Lamb production systems are under increasing pressure to reduce their environmental footprint, particularly greenhouse gas (GHG) emissions such as methane (Garnett, 2011; Gerber et al., 2013; Jones et al., 2014a). In recent years, carbon footprinting of farms and the resultant produce (e.g., meat) has been increasingly used to estimate resultant environmental impacts (Edwards-Jones et al., 2009; de Vries and de Boer, 2010; Röös et al., 2013; Jones et al., 2014b). Calculating a farm's carbon footprint offers the opportunity to identify sources of high emissions as well as compare emissions from different farming systems. However, such approaches rarely consider the carbon footprint of lamb relative to its nutritional density as a food product, as the standard functional unit for expressing lamb carbon footprint is per unit of product, e.g., kg CO_2e/kg of liveweight (lwt) or kg CO_2e/kg of deadweight (dwt; Edwards-Jones et al., 2009; Jones et al., 2014a,b; Ripoll-Bosch et al., 2013). While this mass-based functional unit is useful for comparing efficiencies of different farming systems (Hyland et al., 2016; McAuliffe et al., 2018a), it does not reflect the nutritional value of the product to humans. Several different approaches have been taken to address this, including using a nutritional functional unit to model carbon footprint while considering nutrient density (McLaren, 2021; McAuliffe et al., 2023a).

Ensuring an appropriate nutrient to use as a functional unit is paramount, as this can directly affect carbon footprint calculations. Previous research has used protein as a nutritional functional unit (e.g., Poore and Nemecek, 2018; Xu et al., 2018). Protein as a nutritional functional unit is useful due to simplicities in data processing; however, it can be considered a rudimentary approach as it does not reflect the impact of individual amino acids and intricacies associated with digestion and absorption (Sonesson et al., 2017; McLaren, 2021). Consequently, protein quality has been incorporated into nutritional functional units. For example, McAuliffe et al. (2023b) used an assessment called the Digestible Indispensable Amino Acid Score (DIAAS), which generates a protein quality "adjusted" functional unit. While this is a useful metric for studies comparing a single nutrient, a product's complete nutritive value is not accurately reflected. Nutrition density scores (NDS) provide a single functional unit in which multiple nutrients can be assessed. The most cited approach for using NDS to express emissions is the Nutrient Rich Food (NRF9.3; Fulgoni et al., 2009) scoring system which accounts for nine nutrients including protein, selected minerals and vitamins, polyunsaturated fatty acids (PUFA) and three nutrients which are to be limited, namely, saturated fatty acids (SFA), sodium and added sugars. Given the complexities and importance of carbon footprinting for environmental targets, policy and consumers, the use of an appropriate functional unit is paramount for accurate determination of a product's nutrient density and carbon footprint (Capper, 2021).

Research has identified that while protein and amino acid profiles of meat remain largely constant across the diets on which livestock are reared, fat content and lipid profiles are heavily influenced by animal nutrition (Scollan et al., 2006). Most notably, grass-based systems have been found to have higher levels of omega-3 PUFA than systems feeding concentrates (Fisher et al., 2000; Warren et al., 2008). Omega-3 PUFA is a functional unit of great importance due to its potential health benefits and nutraceutical properties in humans, e.g., reducing the risk of cardiovascular disease and other inflammatory diseases (Swanson et al., 2012). Consequently, omega-3 PUFA as a single nutrient functional unit has been explored to express emissions, particularly when comparing farming systems (McAuliffe et al., 2018b). Lamb production systems also vary across the world, from low-input pastoral systems to higher-input systems feeding concentrates for the latter 'finishing' period. In the United Kingdom, many farms are typically grass-based systems, but some will provide supplementary concentrates and/or forage crops [e.g., swede (*Brassica napus*) or stubble turnips (*Brassica rapa*)] during the autumn/winter finishing period as grass availability and quality reduces (Barry, 2013).

To date, no studies have explored the effect of finishing diets on the carbon footprint of lamb expressed on a nutritional basis. Using data gathered on farms adopting one of four distinct finishing diets and data from the produced meat, this study applies a dual approach to evaluate the impacts of diet on the carbon footprint of lamb expressed on both a mass and nutritional basis, using omega-3 PUFA in 1 kg of fresh muscle as a functional unit.

2 Methods

2.1 Farm data collection

This paper is based on data from a larger 5-year study that included four balanced design trials. The Welsh Lamb Meat Quality Project conducted research trials across the United Kingdom, exploring on-farm and processing factors that may influence meat eating and nutritional quality. The on-farm factors were investigated across four trials, and included treatments of breed type, lamb gender, muscle cut, lamb finishing diet, daily liveweight gain, seasonality, lamb sire, and processing factors including length of meat ageing period, carcass hanging and packaging (Hybu Cig Cymru – Meat Promotion Wales, 2023). Lamb numbers per treatment were balanced within each trial; however, numbers differed across trials due to lamb availability. Trials were conducted with four Protected Geographical Indication (PGI) approved Welsh abattoirs (DEFRA, 2021) that had previous experience of participating in large trials.

The abattoirs identified lamb producers that could supply lambs for the project (based on the specific trials treatments that were required, e.g., supply lambs of a certain sex, finished on specific diets). A minimum of 24 lambs per farm were needed to reach a target slaughter date. The overall study aim was to research Welsh lamb eating quality across the range of systems that reflect production across the year. As such, the diet of the lambs was representative of those at different seasons / time of year. For example, forage-based crops can only be sown and used for finishing lambs at certain times (Hybu Cig Cymru – Meat Promotion Wales, 2018).

Farm data were collected from 33 farms feeding one of four distinct finishing diets: *forage crops* ($n = 5$), *grass* ($n = 7$), *concentrates* ($n = 6$), and *grass and concentrates* ($n = 15$). The *forage crop* diet consisted of brassicas, fodder beet and forage rape. In the *concentrates* finishing system, lambs were all fed indoors on a diet of concentrates, barley, crimped barley or coarse mix, whereas the *grass* and the *grass and concentrates* diets were all fed outdoors and exclusively on grass and grass and concentrates, respectively. Farm data were self-reported by participating farmers using digital farm information surveys. All farms produced lambs to PGI Welsh lamb standards (DEFRA, 2021). In total, there were 60 lambs fed the *forage crop* diet, 90 lambs fed the *grass* diet, 66 lambs fed the *concentrates* diet, and 228 lambs fed the *grass and concentrates* diet (Table 1). Lambs were born between January 2020 and April 2022 and their age was recorded as the number of days between the average lambing date and the date of slaughter. Lambs consisted of several breeds: terminal sire ($n = 382$), hill ($n = 38$) and cross-breeds ($n = 24$). Previous studies have found breed could potentially affect meat-eating quality (Fisher et al., 2000; Arsenos et al., 2002), therefore breed was controlled for in the statistical design of the study. Terminal sire breeds included Aberfield, Abermax, Charollais, Lleyn, Primera, Suffolk and Texel. The hill breed type included Beulah Speckled Face, Welsh Mountain and Torddu. Lambs were a mixture of male (entire $n = 288$; castrated $n = 72$) and females ($n = 84$; Table 1). Individual lamb weights were recorded on a fortnightly basis over the 6-week finishing period to calculate their liveweight gain for that period. In cases where specific data were difficult to obtain or where any data were missing, recently published UK data or standardised estimates were used. This was sourced predominantly from SRUC's Farm Management Handbook (Beattie, 2022) and Feedipedia (Heuzé et al., 2015). For example, data were collected for diet type; however, actual feed consumption was not included. Therefore, assumptions were made on forage and concentrate intake based on example finishing systems and values from SRUC's Farm Management Handbook (Beattie, 2022).

2.2 Carcass data collection

Lambs were selected at the target carcass weight of 16–22 kg and conformation grade of E, U, R and fat class 2, 3 L, 3H (Hybu Cig Cymru – Meat Promotion Wales, 2012). From the farms selected that provided whole farm data, 444 carcasses were available for analysis. Carcasses were weighed directly after slaughter to calculate the killing out percentage (KO%). Three of the largest lamb muscles used in other lamb sensory scientific studies (Bonny et al., 2018; Pannier et al., 2018; MSA, 2019; Pannier et al., 2019) were selected using the Meat Standards Australia cooking protocol, being the *longissimus dorsi* (Loin; $n = 444$), *semimembranosus* (Topside; $n = 203$) and *gluteus medius* (Chump cut; $n = 96$). The *longissimus dorsi* was analysed for all lambs (number of lambs from each diet, breed type and gender can be found in Section 2.1). The *semimembranosus* analysed included 36 lambs fed the *forage crop* diet, 36 lambs fed the *grass* diet, 18 lambs fed the *concentrates* diet, and 113 lambs fed the *grass and concentrates* diet. Lambs from the *semimembranosus* analysed also consisted of several breeds: terminal sire ($n = 173$), hill ($n = 8$) and cross-breeds ($n = 22$). All *semimembranosus* samples analysed came from ram lambs ($n = 203$). Eight days post slaughter, the muscle pH was recorded for each cut. Muscles were stored at −20°C until nutritional analysis.

2.3 Nutritional analysis

Fatty acid composition was determined by the method of O'Fallon et al. (2007). Lean lamb muscle was hydrolysed with potassium hydroxide in methanol. The potassium hydroxide was neutralised, and the free fatty acids methylated by acid catalysis using sulphuric acid. Fatty acid methyl esters were extracted into hexane and analysed by GC-FID using a CP-SIL 88 column (100 m × 250 μm × 0.2 μm). Intramuscular fat was determined by the method of Folch et al. (1956) with the percentage of extracted fat calculated gravimetrically.

For total amino acid analysis, 100 g of fresh muscle was hydrolysed in constant boiling hydrochloric acid. Samples were then dried down, diluted and analysed on a Waters 2,695 pump/injector system. The individual amino acids were separated by ion exchange chromatography on a strong cation exchange resin using sodium citrate buffer gradients of increasing pH. The ninhydrin reagent was pumped using a Waters 1,515 isocratic pump. The ninhydrin reaction occurs in a heated reaction coil at 125°C, and the derivatized amino acids are detected using a Waters 2,487 variable wavelength UV/VIS detector.

Mineral analysis was carried out using a two-stage microwave digestion followed by Inductively Coupled Plasma Optical Emission

TABLE 1 Summary of the mean key performance indicators (± standard error) over the 6-week finishing period and number of farms carbon footprinted for each finishing diet.

	Diet				
	Forage crops	Grass	Concentrates	Grass and concentrates	Value of *p*
No. of farms (No. of lambs)	5 (60)	7 (90)	6 (66)	15 (228)	
Liveweight at start of finishing period (kg)	37.3 ± 0.36[a]	33.0 ± 0.86[b]	35.7 ± 0.27[a]	33.4 ± 0.36[b]	<0.001
Liveweight gain (g/day)	179 ± 8.48[a]	213 ± 11.40[a]	189 ± 10.63[a]	268 ± 8.15[b]	<0.001
Total weight gain over finishing period (kg)	6.7 ± 0.32[a]	8.6 ± 0.48[b]	7.3 ± 0.31[ab]	10.2 ± 0.17[c]	<0.001
Liveweight at slaughter (kg)	44.0 ± 0.29[a]	42.0 ± 0.54[b]	43.0 ± 0.34[ab]	43.6 ± 0.26[a]	<0.01
Killing out percentage (%)	46.6 ± 0.38[a]	45.8 ± 0.56[a]	46.3 ± 0.32[a]	46.8 ± 0.20[a]	>0.05
Carcass weight (kg)	20.5 ± 0.16[a]	19.1 ± 0.21[b]	19.9 ± 0.15[a]	20.3 ± 0.11[a]	<0.001

Different lower-case letters indicate statistically significant differences at the 5% level.

Spectroscopy using wavelengths 238.2 and 213.9 nm for iron and zinc, respectively. ERM-BB184 Bovine Muscle from the Joint Research Centre of the European Commission was used as a quality control material. ISO 17034 certified reference standards for zinc and iron were purchased from ROMIL Ltd., Cambridge, United Kingdom.

The full nutritional analysis methods are available in the Supplementary material.

2.4 Emission estimates

Baseline carbon footprints were calculated using Agrecalc (Agricultural Resource Efficiency Calculator).[1] Agrecalc was developed by Scotland's Rural College and has been found to be among the best-performing carbon accounting tools in terms of transparency, methodology and allocation for use on UK farms (Sykes et al., 2017). The system boundary for Agrecalc is "cradle-to-grave," i.e., all emissions from agricultural production from the birth of the animal to the farm gate. The tool uses methods from the latest 2019 refinements to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and is certified to PAS2050 standards (2011). Agrecalc follows IPCC (2019) Tier 2 country-specific guidelines for all livestock and manure management CH_4 and N_2O emissions. Direct N_2O emissions from soil following fertiliser and manure application also used IPCC (2019) Tier 2 calculations. IPCC (2019) Tier 1 methodology was used to calculate N_2O emissions from crop residues and indirect N_2O emissions. DEFRA, (2021) EFs were employed for calculating emissions relating to energy usage. Emissions for imported feed and embedded fertiliser were based on values from the Dutch Feedprint database (Vellinga et al., 2013) and Kool et al. (2012), respectively. Data required to calculate sequestration estimates were not provided, therefore, carbon sequestration was not considered in this study.

For conversion of non-CO_2 gases, Agrecalc uses the global warming potential over a 100-year period (GWP100) published in the fourth assessment report (AR4) which are consistent with National Inventory reporting. Methane has a GWP100 of 25 and the value for N_2O is 298 (IPCC, 2007). It is important to note that these values are different from those in the most recent assessment report (AR6; IPCC, 2023).

Emissions from Agrecalc were expressed as both GHG emissions per unit of product (i.e., kg CO_2e/kg of deadweight (dwt)) and GHG emissions per unit of nutrition. To calculate the latter, the value of mg omega-3 measured in 100 g of fresh muscle, determined as described in Section 2.2, was converted to the equivalent in g omega-3 in 1 kg of fresh muscle. The calculated GHG emissions per kg dwt were then divided by this to give kg CO_2e/g omega-3, giving the GHG emissions per unit of nutrition.

2.5 Statistical analyses

For individual variables, models were fitted using mixed effects models in R (R Core Team, 2022). Models were fitted using the lme4 package (Bates et al., 2015) and value of *p*s were calculated using Satterthwaite's method from the lmerTest package (Kuznetsova et al., 2017). In all models, Farm was included as a random effect and models included diet, breed type and gender as factors. This approach allowed the analysis of the data that was unbalanced in breed and gender while controlling for any differences in these factors not of direct interest. Gender was not included for the *semimembranosus* models as all the lambs in this group were male. Pairwise differences were calculated using the emmeans package (Lenth, 2023) using a Tukey correction for multiple comparisons. After fitting diagnostic plots for all models were checked for any evidence of heterogeneity of variance or non-normality of errors. For a few variables a log (or log+1) transformation was applied to correct for heterogeneity of variance. Data were plotted using the ggstats package (Larmarange, 2023).

To assess the effect of diet on finishing system performance, a one-way ANOVA and Tukey pairwise-comparison were performed on individual key performance indicators (KPIs). A one-way ANOVA was conducted to assess the effect of diet on mass-based product emissions and a two-way ANOVA was used to test for an association between diet and muscle cut on nutrition-based product emissions. Multiple pairwise-comparison between the means of groups were then performed using Tukey multiple pairwise-comparisons. The level of statistical significance was set at 5% for all tests in this study.

3 Results

3.1 Farm and lamb production data

Lamb growth and weights varied between finishing diets. Lambs from the *forage crops* and *concentrates* diet had significantly higher liveweights at the start of the finishing period compared to lambs on *grass* and *grass and concentrates* diet (Table 1). Lamb age varied at the start of the finishing period to reflect the inherent differences in the production and seasonality of the different finishing systems according to industry practice. Lambs from the *grass and concentrates* diet had significantly higher liveweight gain and total weight gain over the finishing period than lambs from all other diets. Lambs on the *forage crops* diet had the highest liveweight at slaughter whereas the *grass* diet had the lowest liveweight at slaughter (Table 1). Killing out percentages did not vary significantly between diets. Lambs from the *grass* only diet had significantly lower carcass weights compared to lambs on all other diets (Table 1).

Although not directly related to the finishing diet and likely influenced by how lambs were selected, time on farm varied between lambs from different finishing systems. Lambs from the *concentrates* diet were on farm for the longest time (mean 9.2 ± 0.17 months) compared to lambs from: the *forage crops diet* which were on farm for 8.5 ± 0.19 month ($p > 0.05$), *grass* diet which were kept for 6.0 ± 0.22 months ($p < 0.001$) and *grass and concentrates* diet which were on farm for the least time at 5.2 ± 0.11 months ($p < 0.001$).

3.2 Nutritional composition of lamb meat

There was no significant difference between the amino acid content of *gluteus medius* across the four diets (Supplementary Table 1;

1 https://www.agrecalc.com/

$p > 0.05$). As expected, there were also no significant differences found in the iron content of both the *longissimus dorsi* and *semimembranosus* across all four diets ($p > 0.05$), the iron content of muscle is more associated with age than diet (Pannier et al., 2014). Additionally, there was no significant differences in the zinc content in the *semimembranosus* across all diets, however, diet did have an effect on the zinc content of the *longissimus dorsi* ($p < 0.001$).

Fat percentage varied significantly between finishing diets in both the *longissimus dorsi* and *semimembranosus* ($p < 0.05$). Differences were noted in the total fatty acid composition and saturated fatty acid in the *longissimus dorsi* across the four diets ($p < 0.05$); however, there were no differences found in total fatty acid content of the *semimembranosus* across diets (Table 2; discussed in Section 4.1). There were significant differences in the total omega-3 PUFA content in the *longissimus dorsi* across the four finishing diets ($p < 0.001$), with the highest and lowest being reported in muscle from the *grass* and *concentrate* diets, respectively. The analysis controlled for the differences in breed type (*longissimus dorsi* and *semimembranosus*) and gender (*longissimus dorsi* only). There was not a consistent pattern among fatty acids, with breed type and gender being significantly different in some but not all of the variables (full results can be found in Supplementary Table 2). For the variable of interest (omega-3 PUFA), breed type had a significant effect in the *semimembranosus* ($p < 0.05$) but not in the *longissimus dorsi* ($p > 0.05$). There was also a significant difference in omega-3 PUFA between genders in the *longissimus dorsi* ($p < 0.05$).

There were significant differences in levels of palmitic acid (C16:0) and stearic acid (C18:0) across the four diets in the *longissimus dorsi* muscle ($p < 0.05$), with no differences detected in the *semimembranosus* (Table 2). Linoleic acid (C18:2 n-6) was significantly greater in the *concentrate* diet and lowest in the *grass* diet in the *longissimus dorsi* muscle. There was no difference between C18:2 n-6 levels from lamb finished on the *forage crops* and *grass and concentrate* diet.

Lamb from the *forage crops* diet and *grass* diet had significantly higher alpha-linolenic acid (C18:3 n-3) in both the *longissimus dorsi* and *semimembranosus* with levels being reported as 62 and 61 mg/100 g and 71 and 73 mg/100 g, respectively, compared to the *concentrate* diet where 42 mg/100 g was reported for both muscles. There were differences in levels of eicosapentaenoic acid (C20:5 n-3; $p < 0.001$), docosapentaenoic acid (C22:5 n-3; $p < 0.05$) and docosahexaenoic acid (C22:6 n-3; $p < 0.001$) across diets in the *longissimus dorsi* muscle, however, no differences in any long chain omega-3 PUFA was noted in the *semimembranosus*.

Omega-3 PUFA is known to have a variety of health benefits such as reduced risk of cardiovascular disease and other inflammatory diseases (Swanson et al., 2012). Omega-3 PUFA composition of lamb is also known to vary significantly between animal diets, particularly between grass and concentrate feeding (Fisher et al., 2000; Warren et al., 2008). Our finding are in line with other previous studies. Grams of omega-3 in 1 kg of fresh muscle (kg CO_2e/g-omega-3) was selected as a functional unit to express emissions on a nutritional basis.

3.3 Mass-based and nutrition-based product emissions

Mass-based product emissions varied significantly from 21.8–36.4 kg CO_2e/kg dwt across finishing diets ($p < 0.001$). There were significant differences in mass-based product emissions between all diets ($p < 0.05$) apart from the *forage crops* and *grass and concentrates* diets ($p > 0.05$). Lambs from the *concentrates* diet had the lowest average mass-based product emissions (25.0 kg CO_2e/kg dwt) while those from the *grass* systems had the highest (28.1 kg CO_2e/kg dwt; Figure 1; $p < 0.001$). Variation in mass-based product emissions was also seen within the same diets, for example, *grass and concentrates* diet, highest mass-based product emissions (36.4 kg CO_2e/kg dwt) were more than 1.6 times higher than the lowest (22.2 kg CO_2e/kg dwt).

Further variation was seen when accounting for omega-3 content, with nutrition-based emissions ranging from 12.1–73.8 kg CO_2e/g omega-3. Nutrition-based emissions were greater for *longissimus dorsi* than for *semimembranosus* across all diets other than *for grass and concentrates*, although this difference was not statistically significant ($p > 0.05$). Significant differences in nutrition-based product emissions between the two muscle cuts were only found in the *forage crops* diet ($p < 0.01$; data not shown). The *semimembranosus* cut of lambs from the *forage crops* diet had the lowest average nutrition-based product emissions (19.2 kg CO_2e/g omega-3; Figure 1), whereas the *semimembranosus* cut of lambs from the *grass and concentrates* diet had the highest nutrition-based product emissions (29.4 kg CO_2e/g omega-3; $p < 0.001$).

4 Discussion

4.1 Omega-3 PUFA composition

Significant differences were found in the total fatty acid composition and saturated fatty acids in the *longissimus dorsi,* but not in the *semimembranosus* across the four finishing diets. This it is likely due to the *longissimus dorsi* having a higher total fat content than the *semimembranosus* (Supplementary Table 1). Differences were found in the fatty acid composition of the *semimembranosus* across finishing diets, however, these differences were not significant. This may be due to the lower number of *semimembranosus* samples analysed ($n = 203$) compared to the *longissimus dorsi* ($n = 444$), due to this study being part of a larger research trial looking at multiple variables, one being muscle/cut. Nonetheless, significant differences were found in C18:3 n-3 and the n-6/n-3 ratio in the *semimembranosus* of lambs across finishing diets, which was ultimately a key focus of the study.

The total fat content for lamb meat was highest in the *longissimus dorsi* from the *forage crops* diet and lowest in *semimembranosus* from the *grass and concentrates* diet. Pasture feeding is often associated with lower meat fat content as found by Fisher et al. (2000) and Nuernberg et al. (2008), who reported 1963 vs. 1853 mg/100 g and 2,100 vs. 1800 mg/100 g muscle in concentrate- and grass-fed lamb, respectively. Conversely, Demirel et al. (2006) reported lambs finished on grass hay had higher total fatty acid, compared to concentrate feeding. This is similar to the saturated fatty acid composition in the *longissimus dorsi* in the current study, where again the *grass and concentrates* diet was lowest. However, the saturated fatty acid composition did not differ significantly between the diets in the *semimembranosus.*

Levels of C18:2 n-6 were higher in lambs that had been fed *concentrates* as part of or as a sole dietary component. This is unsurprising as concentrates are rich in linoleic acid, whereas grass and forage crops would have relatively low levels. Lambs from the

TABLE 2 Estimated marginal mean (± standard error) fatty acid composition of lamb meat from four finishing diets averaged over breed type and gender for *longissimus dorsi* and breed type for *semimembranosus*.

Fatty acid (mg/100 g)	*Longissimus dorsi*					*Semimembranosus*				
	Forage crops	Grass	Concentrates	Grass and concentrates	Value of *p*	Forage crops	Grass	Concentrates	Grass and concentrates	Value of *p*
C12:0	3.9 ± 1.05^{a}	9.8 ± 0.86^{b}	4.7 ± 0.94^{a}	7.3 ± 0.85^{b}	<0.001	4.5 ± 0.58^{a}	4.3 ± 0.69^{a}	4.8 ± 0.64^{a}	5.2 ± 0.51^{a}	0.484
C14:0	61.8 ± 9.72^{a}	104.5 ± 8.18^{b}	58.4 ± 8.12^{a}	78.4 ± 7.67^{a}	<0.001	58.4 ± 5.25^{a}	55.3 ± 6.21^{a}	57.1 ± 5.76^{a}	54.9 ± 4.62^{a}	0.927
C16:0	720 ± 44.2^{ab}	648 ± 36.6^{ab}	737 ± 38.2^{b}	622 ± 35.3^{a}	0.008	512 ± 41.4^{a}	521 ± 47.7^{a}	465 ± 41.3^{a}	453 ± 34.5^{a}	0.449
C18:0	537 ± 41.3^{a}	463 ± 33.8^{a}	542 ± 36.7^{a}	466 ± 33.3^{a}	0.030	407 ± 39.1^{a}	445 ± 44.2^{a}	342 ± 36.3^{a}	348 ± 31.1^{a}	0.219
C18:1 t11	109 ± 8.04^{ab}	130 ± 6.69^{b}	111 ± 6.87^{a}	107 ± 6.41^{a}	0.006	71.8 ± 10.09^{a}	95.1 ± 11.69^{a}	79.1 ± 10.25^{a}	79.6 ± 8.51^{a}	0.403
C18:1 n-9 cis	$1{,}148 \pm 73.1^{ab}$	$1{,}007 \pm 60.3^{a}$	$1{,}179 \pm 63.8^{b}$	$1{,}016 \pm 58.4^{ab}$	0.011	824 ± 56.3^{a}	885 ± 65.7^{a}	760 ± 58.6^{a}	740 ± 48.2^{a}	0.190
C18:2 n-6	104.6 ± 10.52^{ab}	89.1 ± 8.70^{a}	138.2 ± 9.54^{c}	121.4 ± 8.83^{bc}	<0.001	104.7 ± 15.5^{a}	92.1 ± 17.0^{a}	139.9 ± 12.9^{a}	130.7 ± 11.5^{a}	0.115
C20:4 n-6	44.9 ± 3.32^{a}	41.3 ± 2.73^{a}	45.3 ± 3.00^{a}	41.1 ± 2.74^{a}	0.221	42.3 ± 2.21^{a}	35.3 ± 2.61^{a}	41.9 ± 2.41^{a}	41.9 ± 1.94^{a}	0.080
C18:3 n-3	62.1 ± 4.45^{b}	60.5 ± 3.66^{b}	44.2 ± 4.03^{a}	52.7 ± 3.69^{ab}	<0.001	70.5 ± 8.43^{a}	73.0 ± 8.93^{a}	44.0 ± 6.38^{a}	50.3 ± 5.86^{a}	0.041
C20:5 n-3	26.5 ± 1.56^{bc}	29.4 ± 1.28^{c}	21.7 ± 1.40^{a}	24.1 ± 1.28^{ab}	<0.001	27.1 ± 1.98^{a}	29.7 ± 2.22^{a}	22.7 ± 1.79^{a}	23.1 ± 1.55^{a}	0.054
C22:5 n-3	35.1 ± 1.59^{ab}	34.7 ± 1.30^{b}	30.8 ± 1.41^{a}	31.1 ± 1.28^{ab}	0.009	34.2 ± 2.42^{a}	35.4 ± 2.62^{a}	29.3 ± 1.97^{a}	29.8 ± 1.77^{a}	0.179
C22:6 n-3	8.3 ± 0.90^{a}	12.1 ± 0.76^{b}	5.6 ± 0.82^{c}	7.6 ± 0.78^{a}	<0.001	4.8 ± 0.89^{a}	5.9 ± 0.97^{a}	5.7 ± 0.74^{a}	6.9 ± 0.66^{a}	0.110
Total SFA	$1{,}399 \pm 87.0^{ab}$	$1{,}288 \pm 71.9^{ab}$	$1{,}404 \pm 75.5^{b}$	$1{,}208 \pm 69.4^{a}$	0.031	$1{,}024 \pm 83.1^{a}$	$1{,}061 \pm 95.7^{a}$	902 ± 82.6^{a}	893 ± 69.2^{a}	0.324
Total MUFA	$1{,}236 \pm 75.6^{ab}$	$1{,}089 \pm 62.4^{a}$	$1{,}271 \pm 65.7^{b}$	$1{,}095 \pm 60.4^{a}$	0.008	890 ± 60.0^{a}	946 ± 70.0^{a}	830 ± 62.5^{a}	805 ± 51.4^{a}	0.244
Total PUFA	297 ± 15.0^{a}	274 ± 12.3^{a}	295 ± 13.5^{a}	284 ± 12.2^{a}	0.202	296 ± 28.9^{a}	286 ± 30.9^{a}	299 ± 22.5^{a}	296 ± 20.5^{a}	0.984
Total n-3	132 ± 6.7^{ab}	137 ± 5.5^{b}	102 ± 6.1^{c}	117 ± 5.5^{bc}	<0.001	138 ± 12.8^{a}	146 ± 13.7^{a}	103 ± 10.0^{a}	111 ± 9.1^{a}	0.067
Total n-6	157 ± 13.7^{ab}	138 ± 11.3^{a}	192 ± 12.4^{b}	170 ± 11.5^{ab}	<0.001	153 ± 17.0^{a}	132 ± 18.9^{a}	192 ± 15.0^{a}	178 ± 13.1^{a}	0.086
n-6/n-3	1.2 ± 0.20^{a}	1.0 ± 0.17^{a}	1.9 ± 0.18^{b}	1.4 ± 0.17^{a}	<0.001	1.2 ± 0.22^{ab}	0.9 ± 0.25^{a}	2.1 ± 0.21^{c}	1.8 ± 0.18^{bc}	0.002
PUFA/SFA	0.23 ± 0.025^{a}	0.23 ± 0.020^{a}	0.22 ± 0.022^{a}	0.24 ± 0.012^{a}	0.687	0.29 ± 0.023^{a}	0.25 ± 0.027^{a}	0.33 ± 0.025^{a}	0.32 ± 0.020^{a}	0.038
Total FA	$3{,}080 \pm 167^{ab}$	$2{,}816 \pm 138^{ab}$	$3{,}095 \pm 144^{b}$	$2{,}696 \pm 133^{a}$	0.016	$2{,}291 \pm 165^{a}$	$2{,}398 \pm 191^{a}$	$2{,}117 \pm 166^{a}$	2083 ± 138^{a}	0.404

Different lower-case letters indicate statistically significant differences between diets within each muscle at the 5% level. Total SFA: Σ C6, C8 C10, C11, C12, C13, C14, C15, C16, C18, C20, C22, C23. Total MUFA: Σ C14:1, C15:1, C16:1c9, C17:1, C18:1n-9 t, C18:1n9c, C18:1 t11, C20:1 n-9, C22:1 n-9, C24:1 n-9. Total PUFA: Σ C18:2 t n-6, C18:2c n-6, C18:3 n-6, C18:3 n-3, C20:2, C20:4 n-6, C20:5 n-3, C22:2, C22:5 n-3, C22:6 n-3, Total n-3: Σ C18:3, C20:4, C20:5, C22:5, C22:6 LC n-3: C20:5, C22:5, C22:6, Total n-6: Σ C18:2 t, C18:2c, C18:3, C20:2, C22:2. C20:4. n-6/n-3: calculated by dividing total n-6 by total n-3. PUFA/SFA: calculated by dividing total PUFA by total SFA.

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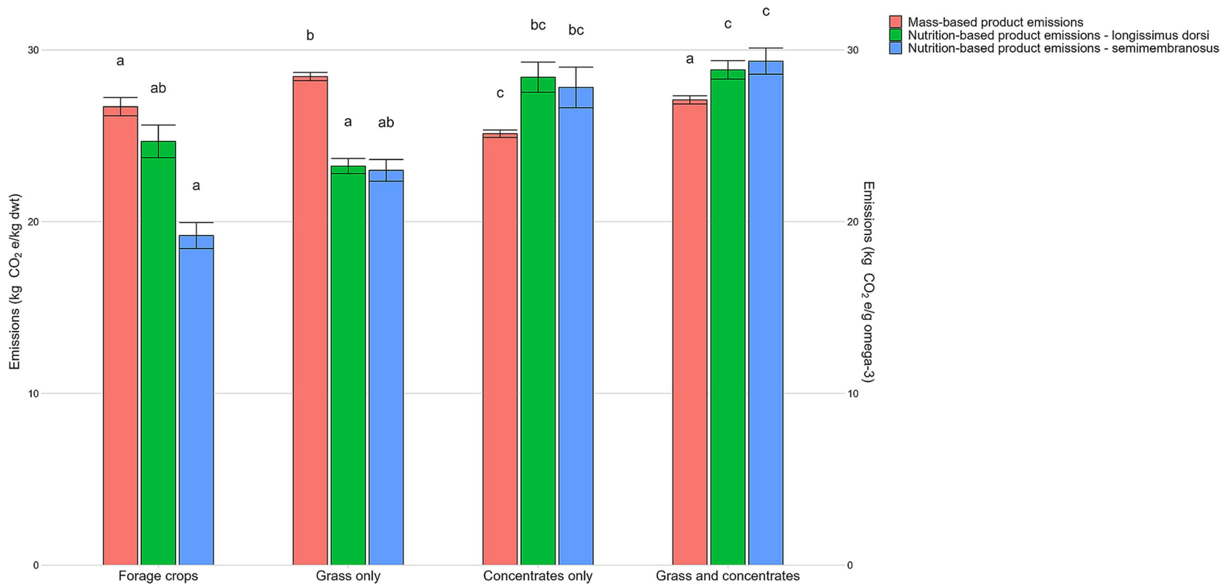

FIGURE 1
Mean emissions estimates (± standard error) for *longissimus dorsi* and *semimembranosus* muscle cuts for each finishing diet expressed as mass-based product emissions and nutrition-based product emissions. Different lower-case letters indicate statistically significant differences in diet within each individual emissions measure at the 5% level.

grass and concentrates diet had significantly less C18:2 n-6 compared to the *concentrates* diet. The mixture of grass and concentrates at dietary components will dilute the amount of C18:2 n-6 being deposited into muscle (Scollan et al., 2017). This dominant C18:2 n-6 influence is also reflected in the n-6/n-3 ratio, which is highest for the *concentrate* diet and lowest for the *grass* diet.

The total omega-3 PUFA composition varied across the four diets, with the *forage crops* and *grass* diet having the highest amount and the lowest being reported in the *concentrates* diet for both muscle cuts. Studies in lamb have reported total omega-3 PUFA as 102 and 44 mg/100 g of meat (Fisher et al., 2000), and 78 and 67 mg/100 g of meat (Kitessa et al., 2010) in animals fed on grass and concentrate diets, respectively. This was supported by a study concluding that lambs reared on grass had significantly higher total omega-3 PUFA levels compared to lambs reared on a grass and concentrate and concentrate and hay diet (Boughalmi and Araba, 2016).

Lamb from the *forage crops* diet and *grass* diet had significantly higher C18:3 n-3 in the *longissimus dorsi* compared to the *concentrate* diet. It is well acknowledged that grass is rich in C18:3 n-3. This is because plant chloroplasts can uniquely synthesise (*de novo*) long chain fatty acids (>18 carbons; Harwood, 1999). Levels of C18:3 n-3 in grass and other plants are influenced by season, species, location and environment (e.g., temperature and light exposure; Elgersma et al., 2003; Mir et al., 2006; Tsvetkova and Angelow, 2010; Yalcin et al., 2011; De Brito et al., 2017). This also explains why forage crops and other plant-based materials have high levels of C18:3 n-3. The 'grass effect' is reflected in the data presented, particularly by the titration effect seen between the *grass*, *grass and concentrates* and *concentrate* diets, where any impact is diluted. There were some significant differences reported for the long chain omega-3 PUFAs (C20:5, C22:5 and C22:6 n-3) across the four finishing diets which is contrary to the findings of others (Fisher et al., 2000; Demirel et al., 2006). Higher levels of long chain omega-3 PUFAs including C20:5 n-3 and C22:6 n-3 were found in the *grass and forage crops* in the *longissimus dorsi*. Although lamb diets consisting solely of grass have very little amounts of long chain omega-3 PUFAs (as pasture species are primarily dominant in C18:3 n-3), small increases are not surprising as conversion of C18:3 n-3 to longer chain omega-3 via elongation and desaturation processes can occur in the lamb (Bessa et al., 2015). Nutrition and genetics are the two most influencing factors affecting fatty acid composition in muscle (Scollan et al., 2014; Dervishi et al., 2019), meaning any variation seen is likely due to lambs being on a grass-based diet more so than the actual species composition in the grazed pastures (Dierking et al., 2010; Scollan et al., 2017).

Due to the differences in omega-3 PUFA composition between the four diets, grams of omega-3 was selected as a functional unit to express emissions on a nutritional basis. While the n-6/n-3 ratio was also considered for use as a nutritional functional unit, we focus on omega-3 PUFA because it accounts for absolute amounts, rather proportions of fatty acids present (EFSA Panel on Dietetic Products, Nutrition, and Allergies (NDA), 2010). Omega-3 PUFA is known to vary between grass and concentrate based diets (Fisher et al., 2000; Warren et al., 2008), and has been previously used as a functional unit to express emissions while comparing farming systems (McAuliffe et al., 2018b). Additionally, omega-3 PUFA is important in human nutrition with documented health benefits such as reducing the risk of cardiovascular disease and other inflammatory diseases (EFSA Panel on Dietetic Products, Nutrition, and Allergies (NDA), 2010; Swanson et al., 2012).

4.2 Mass-based product emissions

Mass-based product emissions varied significantly across finishing systems, which largely reflects the variation in efficiencies between the different diets. The *concentrates* diet had the lowest average mass-based product emissions while the *grass* systems had the highest. Although lambs from the *concentrates* diet were on farm for longer and the bought-in feed would lead to greater embedded GHG emissions, concentrates have a lower fibre content which can result in lower CH_4 production (Yan et al., 2010; van Wyngaard et al., 2018). Lambs on the *concentrates* diet also had higher carcass weights and KO% compared to the lambs form the *grass* diet, resulting in lower emissions per kg of product. Considerable variation was also seen in mass-based product emissions of finishing systems within the same diets. This highlights the difference in efficiencies of finishing systems within the same diet. This could be explained by animal health issues (e.g., lameness or gastrointestinal worm challenge), the quality of the diet offered, and genetic variation.

4.3 Nutrition-based product emissions

The significantly higher omega-3 PUFA content of the *forage crops* diet resulted in the *semimembranosus* cuts from this diet having the lowest nutrition-based product emissions. Similarly, *grass* systems had the lowest nutrition-based product emissions for the *longissimus dorsi* due to lambs from the *grass* diets having the highest omega-3 PUFA content of the *longissimus dorsi*. The *grass and concentrates* diet had the highest nutrition-based product emissions for both the *longissimus dorsi* and *semimembranosus*. This is likely a result of their initially higher mass-based product emissions and relatively lower omega-3 PUFA content compared to that of the *forage crops* and *grass* diets. The *concentrates* diet had lowest omega-3 PUFA content for both the *longissimus dorsi* and *semimembranosus* resulting in higher nutrition-based product emissions. However, as the concentrates diet had the lowest mass-based emissions to begin with, this effect is somewhat masked.

Across all diets except the *forage crops* diet, there was no significant difference in nutrition-based product emissions between the *longissimus dorsi* and *semimembranosus*. This is due to the similar average omega-3 PUFA content between *longissimus dorsi* and *semimembranosus*. For all systems, except for the *grass and concentrate* diet, nutrition-based product emissions were higher in the *longissimus dorsi* than in the *semimembranosus*. This could be explained by the *forage crops* and *grass* diets having higher omega-3 PUFA contents in their *semimembranosus* cuts than in their *longissimus dorsi*. This is likely due to *longissimus dorsi* having a higher SFA and lower PUFA content than the *semimembranosus*. Fowler et al. (2019) also found the *longissimus dorsi* of lambs in extensive systems had lower omega-3 PUFA content than the *semimembranosus*. However, the *forage crops* diet showed significant differences in nutrition-based product emissions between *longissimus dorsi* and *semimembranosus*. This result should be treated with caution due to the small number of farms in this study on the *forage crops* diet as well as the variation of feeds and therefore fatty acid composition of lambs within the *forage crops* diet. For example, the *forage crops* diet consisted of finishing systems feeding brassica, fodder beet and forage rape, which may all affect the nutritional composition of lambs differently. Even within diets that were finished on solely grass, grass quality will vary between farms and therefore this will likely impact the nutritional composition of lambs, particularly omega-3 PUFA content (Howes et al., 2015).

This study found marginally lower nutrition-based emissions for lamb production systems than previous studies. McAuliffe et al. (2018a) noted lambs on upland and lowland systems had nutrition-based emissions of 30.0 kg CO_2e/g omega-3 and 28.7 kg CO_2e/g omega-3, respectively. These values are higher than both cuts from the *forage crops*, *grass* and *concentrates* diets found in the present study. However, these differences must be interpreted with caution as different carbon footprinting tools have been used to calculate emissions estimates in this study. Additionally, our study found higher omega-3 PUFA content in lambs across some diets, e.g., 146 mg/100 g from the *semimembranosus* from the *grass* diet compared to published values, which reported levels of 103 mg/100 g of meat (Whittington et al., 2006).

The present study highlights the importance of nutritional functional unit when considering health and wellbeing implications of products, especially given the diversity in nutritional fatty acid composition in ruminant products. Using omega-3 PUFA as a nutritional functional unit demonstrated its value and warrants further consideration given the numerous reported benefits optimal consumption has on human health and well-being (Jacobson et al., 2012; Givens, 2015; Singh et al., 2016). Although the lamb in this study will unlikely have a nutraceutical effect at a normal portion size, the aim of this study was to explore the effect of finishing diet on the carbon footprint of lamb expressed on a nutritional basis rather than making recommendations on lamb portion sizes.

This study has uniquely used real farm data to highlight the importance of shifting from mass-based functional units to nutrient-based functional units. While mass-based functional units such as per kg dwt still have a valuable place in comparing production efficiencies of farms, they do not reflect the degree of nutrition provided by consumption of the meat produced from each system.

4.4 Limitations

Some appropriate assumptions had to be made to calculate carbon footprints for each finishing system where some farm data were unavailable. For example, although data were collected for diet type, actual feed consumption was not recorded. Although such assumptions and default values regularly have to be applied in farm carbon footprint studies (Edwards-Jones et al., 2009; Ripoll-Bosch et al., 2013; McAuliffe et al., 2018a), there may be an over- and/or under-estimations of emission estimates as a result. Ensuring a larger sample size with an equal number of finishing systems from each diet would reduce unequal variances between diets and improve the statistical power of results. Nonetheless, although breed type and gender were unbalanced between treatments, farms were selected for this study to represent a cross-section of lamb finishing systems, and therefore these differences in production and seasonality are reflected in the results. For example, hill breeds will more likely be associated with grass-based finishing systems as opposed to concentrates. However, for the variables such as breed type (e.g., hill and cross- breeds) which have lower numbers in each group, there will inevitably be a greater level of uncertainty in the results.

Using a single nutrient functional unit does not reflect the products' complete nutritive value. Focusing on a single nutrient functional unit could lead to an under or over-supply of other key nutrients. In this study, we have focused purely on omega-3 PUFA, however, there would likely be variation in a number of other fatty acids between finishing diets, for example, conjugated linoleic acid (CLA) which have a high nutraceutical value. Future studies should therefore consider CLA and indeed the full fatty acid profile. Moreover, lamb can provide a considerable range of nutritional benefits that were not considered in this study. Although many parameters (52 fatty acid parameters, 19 amino acid parameters, and two mineral parameters) were collected for this study, measurement of other key nutrients (e.g., vitamins and certain minerals) would generate a fuller nutrient density score (Fulgoni et al., 2009). Moreover, nutrient density scores often consider the daily recommended intake of each nutrient. Nutrients collected in this study were from 100 g of fresh muscle, so future work would need to consider cooking losses of meat if a nutrient density score was to be created. However, nutrient density scores are not without their limitations. The outcomes of nLCAs which employ a nutrient density score are highly dependent on the nutrients which are included in the metric. This means some metrics are more suitable for some foods than others, and other important aspects of nutrition (such as the bioavailability of nutrients and interaction between nutrients) are not captured (Bianchi et al., 2020). Moreover, foods are rarely consumed in isolation and therefore future nLCA studies should consider nutrition at a diet-level (McAuliffe et al., 2018b). Recently, some studies have taken a novel approach which involves a diet-level assessment that accounts for the foods' effect on human health. For example, Stylianou et al. (2016) developed the Combined Nutritional and Environmental Life Cycle Assessment (CONE-LCA). The CONE-LCA uses a traditional LCA approach and predicts health outcomes following changes in diet, using epidemiological data based on the nutritional quality of food. However, these outcomes will obviously depend on the initial diet and its nutritional status of the individuals making the dietary change.

As with all LCA studies, the results of nLCA depend upon the type of LCA (attributional vs. consequential), where system boundaries are drawn, and the allocation method they employ (Silva, 2021). Clearly, nLCAs also require an extra layer of data relating to the nutritional value of food, introducing additional sources of variation. Studies often rely on a range of external databases for this nutritional information. Although not an issue in this study, data availability and quality are major limitations of nLCA. This includes both primary data from agricultural production and secondary data from agricultural databases. When utilising primary data, there can be concerns of the representativeness of data, particularly if data comes from a single, specific year (Notarnicola et al., 2017). With secondary data, databases exhibit significant variability in terms of detail and completeness and are often biassed towards conventional production in high-income countries (Teixeira, 2015; Carvalho et al., 2023). Moreover, some nLCA studies may require additional information such as nutritional intake recommendation, interactions with other foods, and food processing and preparation (McLaren, 2021). Again, while this was not a limitation in the current study, the lack of available high-quality data will likely limit the wider use and application of nLCA.

Despite the assumptions and limitations of this study, a novel functional unit has been successfully used to compare four finishing diets of lambs and has highlighted the importance of considering nutrition when expressing GHG emissions.

5 Conclusion

This preliminary assessment is the first of its kind to use real farm and carcass data to assess the effect of finishing diet on lamb carbon footprints expressed on a nutritional basis. Despite recognised limitations, this study has demonstrated the need to consider nutrition when expressing carbon footprints. When a mass-based functional unit was employed, *grass* diets had on average the highest carbon footprint, however, when omega-3 PUFA content was accounted for, the *grass* diet had the lowest carbon footprint for the *longissimus dorsi*. While mass-based functional units can be useful for comparing efficiencies of different farming systems, they do not reflect the function of the final product, human nutrition. Therefore, future work should consider both mass-based and nutrition-based functional units when comparing different farming systems. Future studies should also collect a comprehensive set of carcass and nutritional parameters for emissions to be expressed through a full nutrient density score. This would allow us to accurately determine the role nutrient density of a product plays in environmental sustainability of livestock farming.

Data availability statement

The datasets presented in this article are not readily available because the data analysed in this study was obtained from Hybu Cig Cymru – Meat Promotion Wales. Requests to access these datasets should be directed to ET, ethomas@hybucig.cymru.

Ethics statement

The animal studies were approved by Hybu Cig Cymru – Meat Promotion Wales, Ty Rheidol, Parc Merlin, Glanyrafon Industrial Estate, Aberystwyth SY23 3FF. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

LM: Data curation, Formal analysis, Visualization, Writing – original draft. LP: Data curation, Project administration, Writing – original draft. JG: Formal analysis, Writing – review & editing. NS: Funding acquisition, Supervision, Writing – review & editing. AN: Writing – review & editing. ET: Conceptualization, Investigation, Supervision, Writing – review & editing. ES: Data curation, Investigation, Writing – review & editing. CM: Investigation, Resources, Writing – review & editing. AW: Investigation, Resources, Writing – review & editing. SC: Investigation, Resources, Writing

– review & editing. LF: Conceptualization, Writing – review & editing. APW: Supervision, Writing – review & editing.

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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.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1321288/full#supplementary-material

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Enoch Kikulwe,
Alliance Bioversity International and CIAT, Kenya

REVIEWED BY
Eric Brako Dompreh,
WorldFish, Malaysia
Justice Gameli Djokoto,
Dominion University College, Ghana

*CORRESPONDENCE
Nigel Unwin
✉ n.unwin2@exeter.ac.uk
Predner Duvivier
✉ pduvivier@yahoo.com

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Differences in income, farm size and nutritional status between female and male farmers in a region of Haiti

Predner Duvivier[1]*, Robers Pierre Tescar[1], Cassandra Halliday[2], Madhuvanti M. Murphy[3], Cornelia Guell[2], Christina Howitt[3], Eden Augustus[3], Emily Haynes[2] and Nigel Unwin[2,4]*

[1]Faculté d'Agronomie et de Médecine Vétérinaire, Université de d'État d'Haïti, Port-au-Prince, Haiti, [2]European Centre for Environment and Human Health, University of Exeter, Penryn, United Kingdom, [3]George Alleyne Chronic Disease Research Centre, The University of the West Indies, Bridgetown, Barbados, [4]Medical Research Council (MRC) Epidemiology Unit, University of Cambridge, Cambridge, United Kingdom

Introduction: Haiti is the poorest country in the Americas and has the highest levels of gender inequality. It has high burdens of malnutrition and food insecurity. Our aim in this study was to investigate differences between female and male heads of farms in their farm's size and income and in their nutritional status.

Methods: We conducted a mixed-method study with a quantitative survey with 28 female and 80 male farmers and qualitative semi-structured interviews with seven women and 11 men, in nine rural communities, Plateau de Rochelois, Nippes, Haïti.

Results: We found that significant inequalities existed between female and male heads of farms in this region of Haiti. Farm income was associated with farm size, with female farmers having on average smaller farms, and markedly lower farm incomes compared to male farmers, even after adjusting for the fact that their farms were smaller. Male farmers also had more access to seeds, financing and transportation to market. In addition, female farmers had markedly higher levels of overweight and obesity. In both male and female heads of farms around 1 in 20 were underweight.

Discussion: These findings complement those from other settings, showing that female farmers in low- and middle- income countries typically face severe challenges in accessing resources such as land, credit, and inputs, which can limit their productivity and income-generating potential. Gender sensitive interventions to promote farmer health, well-being and productivity are required.

KEYWORDS

small holder farmers, gender, inequalities, nutrition, body mass index, income, Haiti, Caribbean

1 Introduction

Haiti, home to ~11.5 million people in 2022, is the lowest income country in the Caribbean and Latin American region. It has had persistently high levels of food insecurity, with only 57% of its population having access to sufficient food (The World Bank, 2023). The country also faces high burdens of malnutrition, including childhood stunting (22% prevalence), anemia in women of reproductive age (48%), and overweight and diabetes in adults (>50 and 9%, respectively; Country Nutrition Profiles, 2022).

There are more than one million small family farmers, who cultivate on average <1.5 ha of land. Agriculture constitutes the main source of income for about 60% of rural Haitians, accounts for ∼20% of the gross domestic product and employs more than 50% of the active labor force (World Economic Forum, 2011; Bargout and Raizada, 2013; The World Bank, 2023; World Food Programme, 2023). Agriculture has historically played a crucial role in the country's economy and has shaped the landscape through the sector's activities. Haiti covers an area of 27,500 km^2, roughly 60% of which is mountainous terrain. Around 40% of the landmass is used for agriculture (Montgomery, 2007; Bargout and Raizada, 2013). Centuries of colonial exploitation and deforestation, coupled with unsustainable farming practices, have significantly reduced suitable agricultural land available to smallholder farmers today (Smucker et al., 2005; Montgomery, 2007). The resultant deterioration of soil quality impedes crop production and contributes to poverty and malnutrition in Haiti. Many farmers have felt channeled to engage in unsustainable cultivation techniques due to poverty and insufficient resources (Bargout and Raizada, 2013).

The importance of addressing the environmental sustainability and economic viability of food production by small holder farmers for population food security and nutrition in Haiti was given new emphasis in 2018 with the National Policy and Strategy for Food Sovereignty, Security and Nutrition. The policy recognizes the central role of women within the food system, including as farmers, food traders, and guardians of children's diets (Steckley et al., 2023). Globally, it is well-known that there are substantial gender inequalities across food systems, from agricultural production through to retail and consumption, particularly in low and middle income countries (Njuki et al., 2023). Women tend to be disadvantaged in accessing a range of resources, including: knowledge and information, tools and technology, credit, land, time and access to markets (Njuki et al., 2023). Time poverty, related to other roles, such as managing households, childcare and food preparation is another constraint than women face (Arora, 2015; Pathak, 2022). In addition, female small-holder farmers in low and middle income countries tend to be more vulnerable to food insecurity and poor health outcomes compared to their male counterparts (Agarwal, 2012; Botreau and Cohen, 2020).

Gender inequality in Haiti, as assessed by the gender inequality index (United Nations, 2024), is the highest in the Americas and one of the highest in the world. In the work reported here, we use data from a mixed method study of farmers in the Nippes Region of Haiti to investigate differences by gender. We aim to answer the question, are there differences in farm size, produce diversity, income and nutritional status between female and male heads of farms? Through answering this question, we aim to inform further work designed to address gender inequalities amongst small holder farmers in Haiti.

2 Methods

This study was undertaken as part of an international collaborative project (UKRI, BB/T008857/1) between the Universities of the West Indies, South Pacific, Exeter (UK), McGill (Canada), Cambridge (UK) and the State University of Haiti (UEH). The overarching aim of this study was to explore and pilot test approaches to improving local food production and nutrition in Small Island Developing States (SIDS) in the Caribbean and Pacific. In Haiti the project was led from the Faculty of Agriculture and Veterinary Medicine at UEH by PD and RPT. The project area in Haiti was the Plateau de Rochelois, in the Department of Nippes (one of Haiti's 10 administrative Departments).

2.1 Population and sample

Three communes within the Plateau de Rochelois were chosen: Paillant, Anse-à-Veau and Petite-Rivière de Nippes. Sampling and recruitment were purposefully conducted in order to capture the diversity of agricultural activities in these communes. Three communities were randomly selected from each commune, and for the quantitative survey, from each community 12 farmers were identified and recruited, giving 108 in total. Of these, 28 (25.9%) were women and 80 (74.1%) men. These proportions of female and male headed farms are similar to what is found nationally, with it being reported in 2017 that 22% of farms are managed by women (Plantin, 2021).

A sub-set of the quantitative sample was asked for a semi-structured qualitative interview and 18 heads of farms agreed. For the qualitative study and its purposive sample, seven female and 11 male heads of farms agreed to be interviewed.

2.2 Data collection

A quantitative questionnaire was developed and administered to the study participants (i.e., to the head of each farm) to gather comprehensive information about them and their farms. The questionnaire covered a range of socio-demographic characteristics, including age, gender, number of persons per household, and farm revenue. Farm characteristics were also assessed, including farm size, ownership of tools (machete, hoe, pruning knife, and ax), number of different types of crops grown, and number of animals raised. The height and weight of each farmer were measured. Respondents were asked whether they were under treatment for diabetes and raised blood pressure. Income data was collected in local Haitian gourdes (HTG) currency and then converted to US dollars using the exchange rate of 1 USD = 150 HTG.

In the qualitative one-on-one interviews, interviewees were asked about their positive and negative experiences as food producers, the barriers they faced and how these could be overcome, and the relationships between their own food production and nutrition within their households. Both quantitative questionnaire and qualitative topic guide were developed with careful consideration of cultural, linguistic, and literacy factors to ensure that it was clear and comprehensible to all participants. Data collection was conducted by five agriculture Masters students at UEH under the supervision of two lead investigators (PD, RPT).

2.3 Ethical approval

Prior to data collection, ethical approval was obtained from the National Bioethics Committee (CNB) of Haiti, and from the

Research Ethics Committee of the University of Exeter (as the lead institution for the overall project).

2.4 Data analysis

The quantitative data was entered into an Excel spreadsheet and imported into Stata version 17, for cleaning and analysis. Three age groups were created for analysis: 20–39, 40–59, and 60 years and above. Body mass index (kg/m^2) was calculated from height and weight, and three categories created (according to World Health Organization classification criteria): underweight (BMI $<$ 18.5), overweight (BMI $\geq$ 25 to $<$ 30) and obese (BMI $\geq$ 30). For the purpose of examining farm income by farm size in bivariate analyses, three categories of farm size were created: small (0.16 ha $\leq$ FS $<$ 1.13 ha), medium (1.13 ha $\leq$ FS $<$ 2.42 ha), and large (2.42 ha $\leq$ FS $\leq$ 12.09 ha). Two categories of tool ownership were created, those owning all four types of tools (hoe, machete, pruning knife, and ax) and those owning $<$4.

As appropriate to the type and distribution of the data, data is summarized as mean (standard deviation) or median (interquartile range) or proportion (as a percentage). Differences between male vs. female heads of farms are presented with 95% confidence intervals and p-values, with confidence intervals that do not contain 0, and a p-value of $<$0.05 being considered as "statistically significant." Multiple linear regression was used to explore the extent to which male to female differences in farm income were related to other differences in farm characteristics, including farm size (entered as a continuous variable), number of persons on the farm, ownership of tools, number of varieties of crops grown and number of animals.

All qualitative interviews were audio-recorded, transcribed verbatim and translated from Haitian Creole to English. A "follow a thread" mixed-method analysis approach (Dupin and Borglin, 2020) was used, in which findings from one dataset are used to guide analysis in the other. Here, the quantitative analysis, which was carried out first, particularly focused on gender differences for the reasons given in the introduction. Although gender was not explicitly part of the qualitative interview questions, the qualitative analysis of transcripts subsequently focused on different experiences between farmers of different farm size and potential difference between male and female heads of farms. The qualitative analysis was supported by the software Dedoose version 7.0.23 (www.dedoose.com).

3 Results

Quantitative survey data was collected from 108 heads of farms, 28 of which were women and 80 men. Roughly half the men and women were aged between 40 and 59 years. The median farm size was significantly smaller in female (1.1 ha) than in male (1.94 ha) headed farms (Table 1).

Male farmers were older on average than female farmers, they headed households with more members and owned more tools (Table 2). Male farmers also reported growing a greater variety of crops and owning more animals per farm than female farmers (Table 2). The farm income for male headed farms was almost 2½ times greater than for female headed farms (Table 2). The total annual revenue reported by male farmers (i.e., including any additional income from outside farming activities) was almost twice as large as for female farmers (Table 2).

Qualitative interviews were conducted with 18 participants, the characteristics of which are summarized in Table 3.

The qualitative data provide contextual information to these differential experiences, and gave a greater understanding as to how access to land might relate to crop diversity, livelihoods, food security and health. All heads of farms emphasized that their crops at least partly provided main staples for their household—yams, cassava, sweet potatoes, taro, leeks, carrots, bananas, beans etc., and generally crops rather than livestock (such as chickens, cows, pigs, or goats) are for household consumption. What type of crop could be cultivated, however, was discussed by heads of small farms as being limited by land availability.

> Farmer (3; female, 40+ years old, small farm): I raise cows, goats. Now, it's not raining, it's carrots, yams, beans. I do not plant cabbage.
>
> Interviewer: Why are you doing this?
>
> Farmer: I do it because it's the easiest thing for me to do. We don't plant the cabbage because we don't have land for it. We cannot grow cabbage in the land we have.

Other facilitators that interviewees mentioned for the types and varieties of crop that could be grown included access to training, availability of seeds of specific crops that were considered favorable, and availability of financial assistance such as "micro-credit." These were mainly discussed by the male farmers. All farmers, including from small sized farms, explained in their interviews that they sold livestock and surplus crops at market, although this was heavily dependent on access to transportation needed to get produce to market. It was clear that male farmers had greater access to transportation options and could therefore more easily sell at market and reap the benefits of additional income for household expenses such as for children's education and healthcare. Additionally, while over half the men spoke about sources of income from other jobs and activities, only one woman described additional income beyond selling at market.

> Farmer (8; male, under 40, small farm): I grow cabbage, carrots, yams, sweet potatoes. I raise cows. After I'm also a builder and a taxi driver too.

The relationships between farm income, gender and farm size were further explored in the quantitative survey data. Firstly, an analysis stratified by three levels of farm size was conducted (Table 4). At each level income is significantly higher in men compared to women.

Secondly, multiple linear regression was undertaken, with farm income as the dependent variable. The following independent variables were examined: gender, farm size (as the continuous variable, not the three categories in Table 4), age, number of persons per household, owning at least four types of tools (as a dichotomous, yes/no, variable), number of types of crops and number of animals. Those variables that were statistically significantly related to farm income in unadjusted analyses were

TABLE 1 Number of participants by age, gender and farm size, and showing the difference in farm size between men and women.

	Men		Women		M minus W diff in farm size	
Age Grp	*n*	Farm size (Ha)[a]	*n*	Farm size (Ha)	Ha (95% CI)	*p*-value
20–39	23	1.61 (0.89, 2.56)	12	1.21 (0.84, 1.87)	0.4 (−0.81, 1.46)	0.56
40–59	41	2.04 (1.45, 3.23)	15	0.97 (0.67, 1.29)	1.07 (0.19, 1.94)	0.018
60+	16	1.93 (1.61, 3.02)	1	0.89 (-)	1.04 (−5.32, 7.41)	0.73
All	80	1.94 (1.45, 3.06)	28	1.10 (0.73, 1.64)	0.84 (0.21, 1.40)	0.009

Figures are median (interquartile range) unless otherwise stated.
[a]Hectares.

TABLE 2 Comparison of selected characteristics by gender of the head of the farm.

	Men	Women	M minus W	
			Diff (95% CI)	*p*-value
Age (years)	47.7 (11.7)	41.4 (10.6)	6.3 (1.3, 11.3)	0.0137
Persons per household	6.4 (1.9)	5 (1.2)	1.4 (0.7, 2.2)	0.0002
No. types of crops grown	10.6 (1.1)	9 (1.3)	1.6 (1.1, 2.1)	<0.0001
Animals per farm	16.5 (11.5, 24)	10 (6, 16)	6.5 (1.5, 12.5)	0.012
At least four types of tools (%)	53.8	0	53.8 (42.8, 64.7)	<0.0001
Annual farm revenue (USD)	2,945 (2,340, 3,795)	1,198 (1,092, 1,712)	1,747 (1,291, 2,208)	<0.0001
Annual total revenue (USD)	3,540 (2,795, 4,342)	1,930 (1,343, 2,687)	1,610 (1,006, 2,205)	<0.0001

Figures are mean (SD) or median (interquartile range) unless otherwise stated.

entered together into the final regression model (Table 5). After adjusting for other farm characteristics, the average annual farm revenue for male headed farms was almost 750 USD more than for female headed farms. The results in Table 5 also show that farm size is an independent predictor of farm income: on average an additional hectare of farm size is associated with around 228 USD more in annual income.

With one exception, all of the other male to female differences shown in Table 2, also persisted after controlling for differences in farm size. After adjusting for farm size, male headed farms had 1.1 (95% CI 0.4–1.9, $p < 0.001$) more persons per household and grew 1.4 (0.9–1.9, $p = 0.004$) more types of crops than female headed farms. Among men, farm size was associated with tool ownership, with 21% of men heading small farms owning at least four types of tools compared to 87.5% of men heading large farms ($p < 0.001$). However, irrespective of farm size, all female farmers owned <4 types of tools. The exception was the number of animals. Male to female differences in the number of animals owned became non-significant when controlling for farm size ($p = 0.169$).

The qualitative interviews provided insights on difficulties experienced by the respondents. Most heads of farm regardless of gender—and most of them having grown up in farming families—pointed to increasing challenges to their livelihoods.

> Farmer (1; male, under 40, small farm): For a long time, it was more for own consumption we used to produce. For example, sweet potato has become so expensive that we have to sell it to the schools that buy them from us [rather than eat ourselves]. And the climatic season has become a problem: as now there is no rain, all fields fall to waste. Since the garden is wasted, the misery will increase. So we have become unable to produce either for yourself or for sale.

Such environmental change with increased flooding and droughts, degradation of soil, rising costs of fertilizer (and concerns about health impacts of fertilizer and pesticide use) were seen as important challenges to the resilience of their livelihoods and food security. In addition, rising costs of produce at market but also rising costs of transport to get produce to market, were seen as threats.

Anthropometric characteristics are compared in Table 6. Over two thirds of the women were overweight or obese, compared to around a quarter of the men. Roughly 1 in 20 of the men and women were underweight, with a BMI of <18.5. No woman reported a diagnosis of diabetes, whereas 6 (7.5%) men did (Table 7). A diagnosis of hypertension was reported by just under 1 in 5 men and by 1 in 10 women.

The qualitative interview data found that despite their own food production, imported and processed foods were a significant portion of farmers' diets. All farmers bought additional staples from market, mainly carbohydrates such as rice, flour, corn and spaghetti. Most farmers would have food prepared from what they produced for morning meals, while they would use foods from the market in the evening, to allow for a variety of types of meals, while acknowledging that when income was scarce, they would have to depend more on what they grew to

TABLE 3 Characteristics of the participants in the qualitative study.

Gender	Age (year)	Large farm size[a]	Medium farm size[a]	Small farm size[a]	Total
Men	40 or more	2	3	1	6
Men	<40	0	1	4	5
Women	40 or more	1	2	2	5
Women	<40	0	2	0	2
Total		3	8	7	18

[a]See text in Methods section for definitions.

TABLE 4 'Comparison median farm income by farms headed by men and women, stratified by farm size.

Farm size[a]		Men	Women	M minus W	
				Diff (95% CI)	p-value
Small	n	19	16		
	Income (USD)	2,195 (1,758, 2,536)	1,156 (1,014, 1,353)	1,039 (598, 1,475)	<0.0001
Medium	n	37	8		
	Income (USD)	2,748 (2,104, 3,209)	1,619 (1,400, 2,002)	1,129 (512, 1,730)	0.001
Large	n	24	4		
	Income (USD)	4,362 (3,563, 4,830)	1,585 (1,126, 2,323)	2,777 (604, 3,999)	0.01

Figures are median (interquartile range) unless otherwise stated.
[a]See text in Methods section for definitions.

feed themselves and their households (10; female, <40, medium size farm):

> In the morning we can eat foodstuffs like the yam [from farm]. In the afternoon we cook rice or corn. It's like that all week… In this way we also don't have money to make food, it's the foodstuff, we eat in the morning and in the afternoon… So it is the food in the garden that I eat the most, and the food in the garden is always better.

When asked about the relationship between their own food production and health, what was said mainly related to food security, "because it sustains our life" (3; female, over 40, small farm), but it was also opined that what they grew had more nutritional value than what they could buy (14; male, over 40, large farm):

> I must give more value to my product because I know how to make it, I rely more on it than what they can give me. There are some types of products they [market] can give me that will not be good for my health.
>
> "It is natural, but it will bring health benefits. Because we get a vitamin in it, it has no chemicals" (6; female, over 40, medium farm).

Farmers brought up the use of pesticides and chemical fertilizers and their relationship to the nutritional value of their produce. Some noted that these were necessary to grow their own produce, which is healthier than processed foods. However, others were more ambivalent, noting that pesticides and chemical fertilizers could negatively affect health.

> It's a bit difficult because of the fertilizers we use because it is a chemical product. But economically it is good even if it is not too good for our health…
>
> But we have to put it on to grow enough (5; male, over 50, medium size farm).

4 Discussion

Gender inequality in Haiti, as assessed by the gender inequality index (United Nations, 2024), is one of the highest in the world. Recent national policy recognizes the central role that women play in the food system, and the need to promote greater gender equality (Steckley et al., 2023). Within this context, we use data from our mixed-method study in the Nippe Region of Haiti, to investigate whether there are differences in farm size, produce diversity, income and nutritional status between female and male heads of farms. We find that on average female heads of farms have smaller farms, grow a lower diversity of crops, have fewer livestock and a lower number of farm tools. Female heads of farms had markedly lower income, even after adjusting for differences in farm size. Our assessment of nutritional status, based on body mass index (BMI), indicated that roughly one in 20 women and men were underweight. However, overweight and obesity was experienced by two out of three women compared to one in four men.

4.1 Revenue and productivity in female and male farmers

Our findings of gender disparities in farm size, revenue, and resources are consistent with those from studies in other low

TABLE 5 Predictors from multiple linear regression of annual farm income (in USD).

Variable	B (95% CI) unadjusted	*p*-value	B (95% CI) adjusted[a]	*p*-value
Gender (m vs. f)	1,614.4 (1,069.4, 2,159.2)	<0.0001	749.1 (137.2, 1,361.0)	0.017
Farm size (Ha)	436.5 (311.7, 561.3)	<0.0001	228.4 (86.0, 370.8)	0.002
Age (years)	13.6 (−9.9, 37.0)	0.253	-	
Persons per household	228.1 (82.2, 374.0)	0.002	−19.3 (−147.8, 109.1)	0.766
At least four types tools	1,422.2 (931.9, 1,912.5)	<0.0001	540.4 (14.9, 1,066.0)	0.044
No. types of crops	419.4 (232.8, 606.0)	<0.0001	125.6 (−66.7, 317.8)	0.198
No. animals	43.4 (23.2, 63.6)	<0.0001	21.8 (4.1, 39.6)	0.017

Figures are beta regression coefficients (95% confidence intervals) unless otherwise stated.
[a]All variables entered together into the adjusted model. Age not included in the adjusted model as not associated with income in the unadjusted analysis. Farm size entered as a continuous variable.

TABLE 6 Anthropometric characteristics of male and female heads of farms.

	Men	Women	M minus W	
			Diff (95% CIs)	*p*-value
Height (m)	1.67 (0.06)	1.61 (0.07)	6.3 (0.04, 0.09)	<0.0001
Weight (Kg)	64.6 (7.7)	66.7 (12.7)	−2.2 (−6.2, 1.8)	0.288
BMI (Kg/m^2)	23.1 (2.5)	25.7 (4.3)	−2.6 (−3.9, −1.3)	0.0002
Underwt (BMI < 18.5)	5%	7.1%	−2.1 (−12.8, 8.5)	0.67
Overwt (BMI ≥ 25- < 30)	23.8%	57.1%	−33.4 (−54, −12.8)	0.0012
Obese (BMI ≥ 30)	1.3%	10.7%	−9.5 (−21.1, 2.2)	0.0225

Figures are mean (SD) unless otherwise stated.

TABLE 7 Percentage (95% confidence intervals) of men and women reporting a diagnosis of diabetes and hypertension.

	Men	Women
Diabetes	7.5% (3.4, 15.8)	0
Hypertension	18.8% (11.6, 28.9)	10.7% (3.5, 28.7)

and middle income countries, as described in a recent systematic scoping review (Njuki et al., 2023), and with findings from a recent gender analysis conducted in Haiti and focussed on agricultural development (Kellum et al., 2022).

Across a broad range of settings, consistent difficulties are faced by female compared to male farmers (Njuki et al., 2023). These include, but are not limited to: social norms and roles restricting freedom of movement and access to transport; greater barriers in accessing finance and credit; institutional barriers to accessing information and agricultural technologies; and less access to land. The recent gender analysis from Haiti (Kellum et al., 2022) finds disadvantages for women compared to men that include: worse access to credit, due to gender discrimination by lending institutions; worse access to technical assistance and training; and much less involvement in cattle value chains related to less mobility due to other roles and responsibilities.

Although we do not have data from our study on factors such as differential access to finance, knowledge and technology, it is reasonable to hypothesize that these factors contributed to the gender disparities found. Data from the qualitative part of our study do suggest that male, compared to female, heads of farms have greater access to transport and thus greater opportunity to sell produce at market. The qualitative data also suggest that male farmers were more likely to have additional sources of income from other types of work. Female heads of farms in Haiti, as in other settings (Njuki et al., 2023), typically have additional responsibilities, including childcare and food preparation, responsibilities that are not remunerated and limit opportunities for other employment.

There is evidence from other low and middle income country settings that women farmers on average have lower crop yields than men, significantly affecting their income and economic opportunities. For example, in a study in Ethiopia, the gender yield gap for Maize ranges from 10 to 30%, meaning that women farmers typically produce 10–30% less Maize per hectare than their male counterparts (Gebre et al., 2021). The United Nations Food and Agriculture Organization estimates that on average women-run farms produce 20–30% less than farms run by men (Food and Agriculture Organization of the United Nations, 2011). These gaps in productivity can be attributed to various factors, including limited access to inputs and resources, lower levels of education and training, and social norms prioritizing men's agricultural activities over women's. Our findings are broadly consistent with this picture of lower productivity. We found that female farmers on average had smaller farms, grew fewer types of crops and owned a smaller number of animals. Even when controlling for differences in farm size between female and male farmers, and differences in other factors related to income, such as number of animals and tools owned, female farmers earned significantly less than their male counterparts.

4.2 Nutritional status in female and male farmers

Our study's results indicate significant gender disparities in the nutritional status of farmers in this region of Haiti, particularly women who had a notably higher mean BMI than men, and associated levels of overweight and obesity. Our findings are consistent with the observed differences by gender in BMI, overweight and obesity in the Caribbean as a whole (Guariguata et al., 2018), where women typically have higher BMI, overweight and obesity than men. Compared to recent national estimates for Haiti, our study sample had slightly lower prevalence of obesity and slightly higher prevalence of underweight (Country Nutrition Profiles, 2022). In other parts of the Caribbean, women on average have lower levels of physical activity than men which may contribute to higher levels of overweight and obesity (Guariguata et al., 2018). We did not collect data on physical activity in this study, and so are unable to comment if this is the case here. Data from the qualitative part of the study suggest that processed foods make up a significant proportion of the diet, however, we did not collect dietary data to enable us to quantify this contribution. Whether there are differences in diet between women and men that contribute to the differences in obesity requires further investigation.

From our study, we can only report self-reported diagnosed diabetes and hypertension. These were higher in men than women. In studies where blood glucose and blood pressure are measured, diabetes (the predominant form of which is type 2) in the Caribbean tends to be higher in women (Guariguata et al., 2018) and hypertension similar or higher in men (Howitt et al., 2015; Country Nutrition Profiles, 2022). Recent estimates for the whole of the Caribbean, for example, give a prevalence of hypertension of 22.9% in men and 19.1% in women (Country Nutrition Profiles, 2022). We are unable to say whether the findings in our study represent differences in access to health care, with men being more likely to be diagnosed than women. Further investigation would be required to objectively (e.g., through the measurement of blood glucose and blood pressure) determine the prevalence of diabetes and hypertension in female and male farmers in our study.

4.3 Strengths and limitations

The main strength of this study is that it contributes to the literature describing inequalities between female and male farmers in low and middle income country settings, and does so with data from a country and region with relatively little published evidence on such differences (Njuki et al., 2023). The approach to sampling aimed to achieve a representative sample of farms within the Plateau of Rochelois in Haiti. Although we do not have access to underlying data from that area to compare our sample to, it is reassuring that the proportion of female headed farms in our study (26%) is not dissimilar to that described for Haiti as a whole (22%) (Plantin, 2021). In addition, although the study sample size is relatively small, the differences found between female and male headed farms are statistically robust.

The major limitation of our study is that we have limited data to explore potential determinants of the gender inequalities that we describe. In addition, it is important to acknowledge that the gender differences described here are between female and male heads of farms, and not between all women and men working on farms. We must also acknowledge that our study was based in one area (Plateau of Rochelois) of one region (Nippes) of Haiti, and it is theoretically possible that the type and size of gender inequalities between farmers may be different in other parts of Haiti. Finally, we note that the data collected in this study are as reported to the interviewers by the respondents. It is conceivable, although unlikely in our view, that there are systematic differences in the way the female and male farmers answered the questions posed. Whether or not this is the case would require further investigation.

4.4 Implications for future work

Our findings emphasize the importance of considering and addressing gender inequalities in measures designed to improve the situation of farmers, food security and food sovereignty in Haiti. In order to do this further work is required to better understand the underlying causes of the inequalities we describe. A recent gender analysis from Haiti identified the impacts of potentially differential access by gender to finance, technical assistance, and livestock value chains (Kellum et al., 2022). Further work examining the barriers female farmers face is needed to help inform gender sensitive interventions. Involving female farmers in the design of interventions to improve food production and sustainability is crucial, but remains an under researched area globally (Njuki et al., 2023). Finally, addressing the gender differences in overweight and obesity requires initially a better understanding of what underlies them, from potential differences in diet and physical activity, through to their social and economic determinants.

5 Conclusion

In this paper we demonstrate marked differences across several parameters, including farm size, income and crop diversity between female and male farmers in one region of Haiti. Our findings add to an international body of literature on gender inequalities in access to agricultural resources and incomes. Low female participation in agriculture has been described across the Caribbean (Landportal, 2019). Further work is needed on how to design and implement interventions to successfully overcome barriers female farmers face in Haiti and other parts of the Caribbean. Such work should benefit not only female farmers, but also their dependents and the food security and sovereignty of the wider population.

Data availability statement

The raw quantitative data supporting the conclusions of this article can be made available by the authors on reasonable request. The qualitative data has been collected in a small setting and is therefore not fully anonymous. The corresponding author can be contacted to discuss limited access to the transcripts.

Ethics statement

The studies involving humans were approved by the Comite National de Bioethique (Haiti) and the University of Exeter Medical School Research Ethics Committee (United Kingdom). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

PD: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing—original draft, Writing—review & editing. RT: Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Writing—original draft, Writing—review & editing. CHa: Writing—original draft, Writing—review & editing. MMM: Conceptualization, Methodology, Formal analysis, Writing—original draft, Writing—review & editing. CG: Conceptualization, Funding acquisition, Methodology, Formal analysis, Writing—review & editing. CHo: Formal analysis, Methodology, Writing—review & editing. EA: Formal analysis, Writing—review & editing. EH: Conceptualization, Funding acquisition, Methodology, Writing—review & editing. NU: Conceptualization, Formal analysis, Funding acquisition, Writing—original draft, Writing—review & editing.

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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

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EDITED BY
Ty Beal,
Global Alliance for Improved Nutrition,
Switzerland

REVIEWED BY
Edward Joy,
University of London, United Kingdom
Ejovi Akpojevwe Abafe,
Sustainable Nutrition Initiative hosted by the Riddet Institute, New Zealand
Raquel Lozano,
Massey University, New Zealand

*CORRESPONDENCE
Kate Wingett
✉ kwin5980@uni.sydney.edu.au

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Quantifying pre-consumer food and nutrient losses from the Australian lamb and sheep meat value chain: a case study

Kate Wingett[1]* and Robyn Alders[2,3,4]

[1]Faculty of Medicine and Health, University of Sydney, Sydney, NSW, Australia, [2]Global Health Programme, Chatham House, London, United Kingdom, [3]Development Policy Centre, Australian National University, Canberra, ACT, Australia, [4]Institute for Climate, Energy and Disaster Solutions, Australian National University, Canberra, ACT, Australia

To achieve sustainable development, United Nation members have agreed to reduce food loss along the pre-consumer food supply chain. Food loss and waste is a significant challenge facing Australia and the world, with an estimated one third of all food produced locally being lost or wasted. Globally, Australia is the second largest producer of sheep meat and, locally in Australia sheep meat is the second largest meat industry. Previous assessments of Australian livestock industries estimate low levels of food product losses from the sheep meat chain. This case study aimed to quantify nutrient losses at the point of slaughter of Australian lambs and sheep, using a mass balance approach with secondary data. The results from this study align with this previous assessment with respect to the level of products and nutrients downgraded at the point of slaughter, except for the impact of cadmium contamination on adult sheep liver and kidney downgrades. In turn, cadmium contamination emerged as a key contributor to micronutrient losses, notably dietary folate equivalents, and vitamin A retinol equivalents (RE). There was moderate to high uncertainty in the outputs of the assessment, predominantly due to the absence of data. Addressing these challenges, particularly the absence of offal production data, is crucial as it influences the overall accuracy of the results. This study identifies areas for improvement in the Australian sheep meat value chain, including data governance, at both the macro and micro levels. It also serves as a foundational step in understanding how reducing food and nutrient losses in the Australian sheep meat value chain could contribute to food security and nutrition goals.

KEYWORDS

nutrient, food loss, Australia, sheep, lamb, abattoir

1 Introduction

In 2015, all United Nations members adopted the 2030 Agenda for Sustainable development(United Nations, 2015). The Agenda includes 17 Sustainable Development Goals (SDGs) that form a framework to achieve global health of people and the planet, both now and for future generations (United Nations, 2015). Achieving SDG 12, "responsible consumption and production patterns," will optimize the use of natural resources and indirectly help to protect soils, water, the atmosphere and biodiversity, while simultaneously assisting with food security, nutrition and potentially, the economy (Food and Agricultural Organization, 2019). According to Food and Agricultural Organization (2009) "Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life. The four pillars of food security are availability, access, utilization, and stability. The nutritional dimension is integral to the concept of food security".

Despite Australia being one of the most food secure countries in the world, food insecurity affects a not insignificant proportion of the population. In the Australian Health Survey 2011–13, approximately 4% of respondents reported having run out of food and not being able to buy more food (Australian Bureau of Statistics, 2013b). It is thought the level of food insecurity in Australia is under-reported due to the sensitive nature of the question and the exclusion of homeless and very remote populations from the survey (Booth and Smith, 2001; Australian Bureau of Statistics, 2013b). Bowden (2020) found the level of food insecurity in the general population of Australia ranged from 4 to 13%. This review also noted that there was no regular monitoring of food security levels in the Australian population. The Foodbank Hunger Report presented a worsening picture with 3.7 million Australian households (approximately 36%) reporting food insecurity during 2022 (IPSOS, 2023).

Food insecurity has been negatively associated with health outcomes in children and the elderly in the United States (Gundersen and Ziliak, 2015). Canadian adults and adolescents who experienced food insecurity were more likely to suffer from nutrient inadequacy than those living in food secure households (Kirkpatrick and Tarasuk, 2008). Concurrently, it is estimated that 25% of pregnant women in Australia are anemic, with an estimated half of anemia cases worldwide being caused by iron deficiency (World Health Organization, 2020). Due to the public health impacts of micronutrient deficiencies in the Australian population, there is mandatory fortification of staple foods with folic acid, iodine, thiamine (B1) and vitamin D (Food Standards Australia New Zealand, 2019b).

Reducing food loss and waste has potential to positively impact food security and nutrition (Food and Agricultural Organization, 2019). Target 12.3 of SDG 12 is to halve retail and consumer food waste and reduce food loss along each step of the supply chain (United Nations, 2015). Globally and in Australia, it is estimated that one third of food produced is lost or wasted (Food and Agricultural Organization, 2011; Commonwealth of Australia, 2017). It is recognized that post-consumer food waste is collectively greater in quantity than pre-consumer food loss (Food and Agricultural Organization, 2011; ARCADIS, 2019). However, reducing pre-consumer food losses may still make a valuable contribution to achieving food security and optimizing natural resource management. Kuiper and Cui (2021) predicted, via modeling, that a 25% reduction in food loss in Australia, would lead to a reduction in primary production, land use and greenhouse gas emissions associated with food production, while simultaneously increasing food accessibility, availability of macro- and micronutrient, and increasing gross domestic product. Research on the role of reducing food loss and waste to achieve food security in Australian is very limited at this point in time and there is opportunity to explore this area further (Lai et al., 2022).

There are challenges in estimating food loss and waste and assessing its impact on the economy, community, and environment (Food and Agricultural Organization, 2011; Cattaneo et al., 2021; Hoehn et al., 2023). These challenges include defining what is considered food loss and waste, data availability, and balancing public benefit and private cost in setting policy. To assist with some of the measurement challenges, the Global Food Loss Index has been developed as the indicator to monitor the world's progress toward the target of reducing food loss. In this indicator, food losses are defined as "all the crop and livestock human-edible commodity quantities that, directly or indirectly, completely exit the post-harvest/slaughter production/supply chain by being discarded, incinerated or otherwise, and do not re-enter in any other utilization (such as animal feed, industrial use, etc.), up to, and excluding, the retail level. Losses that occur during storage, transportation, and processing, also of imported quantities, are therefore all included. Losses include the commodity as a whole with its non-edible parts" (Food and Agricultural Organization, 2018).

The Australian Government (2024) has not published results on the contribution of Australian food loss to this indicator. According to the FAOs Food Loss and Waste Database (Food and Agricultural Organization, 2023d) and the FAOs Supply Utilization Accounts / Food Balance Sheets (Food and Agricultural Organization, 2023a), the two datasets used in modeling food loss for the Global Food Loss Index (Food and Agricultural Organization, 2023c) there are zero recorded losses of Australian sheep meat and edible offal or diversions of these products to animal feed or non-food uses. This is as the scope of "loss" in the Food Balance Sheets starts post-slaughter and "food" is defined as products that have been produced with the intention of being consumed by people (Food and Agricultural Organization, 2021d).

There has been a national baseline assessment of food loss and waste published (ARCADIS, 2019), based on the Food Loss and Waste Standard (Food Loss and Waste Protocol, 2016). The majority of food losses from livestock value chains were reported to occur during processing at the abattoir (ARCADIS, 2019).To date, these losses have been measured based on weight of product and/or economic value (Lane et al., 2015; Byran et al., 2016; ARCADIS, 2019; Shephard et al., 2022). Losses from the livestock industries were reported aggregated, including cattle, sheep, and pigs. A total of 123 kilotonnes of livestock products was reported as lost during manufacturing in base year 2015; accounting for approximately 2% of the supply of livestock products (ARCADIS, 2019). Food losses from the Australian livestock chains excluded all materials being diverted to pet food (ARCADIS, 2019) due to the inability to differentiate whether product food products downgraded to animal feed were destined for livestock or pet food supply chains (ARCADIS, 2019).

Animal source foods, including meat and offal, are energy and nutrient dense foods, rich in protein and micronutrients, including iron, zinc and vitamin B12, in high bioavailable forms (Murphy and Allen, 2003; Drewnowski and Fulgoni, 2008; De Bruyn et al., 2020; Beal and Ortenzi, 2022). Globally, food-based dietary guidelines include animal-source foods as part of a healthy diet (Food and Agricultural Organization, 2021a). Australian mutton, meat from an adult sheep, is more micronutrient dense than lamb, beef, pork or chicken meat (Williams et al., 2007) and lambs' liver and kidney are more micronutrient dense than mutton (Wingett et al., 2018). According to Supply and Utilization Accounts, each Australian has approximately 32 g of sheep meat available each day (Food and Agricultural Organization, 2023a). According to the Australian Dietary Guidelines, this level of food supply accounts for approximately one-third of the recommended upper intake of lean red meat for Australian adults (National Health and Medical Research Council, 2013).

Australia is the second largest sheep meat producer in the world by weight (Food and Agricultural Organization, 2023b) and sheep meat is the second largest meat industry in Australia, based on weight of product and gross economic value of carcases from slaughter (Australian Bureau of Statistics, 2022b). In financial year 2021–2022, there were approximately 70 million head in the national flock and 31,000 businesses in the industry (Australian Bureau of Statistics, 2023). The industry produced 513 kilotonnes (kt) of lamb carcase meat (meat from young sheep without any adult teeth in wear, typically up to 1 year old) and 164 kt of mutton carcase meat (meat from animals with at least one adult tooth in wear, typically 1 year-old or more) that was fit for human consumption. The majority of both lamb meat and mutton meat is exported (ABARES, 2020). Reducing pre-consumer food losses from the Australian sheep meat value chain has potential to significantly impact nutrient availability for both Australians and in those countries receiving Australian grown sheep meat and offal.

This study aimed to quantify the loss of nutrients from the direct human food chain at Australian sheep abattoirs and explore the underlying reasons for the nutrient losses, using national datasets. Better understanding of the quantity of food losses, with respect to nutrient composition and cause, is important to both sustainable management of nutrient flows to and from livestock production systems and to support food security through increasing nutrient-dense food availability at the societal level.

To contextualize the effect of the direct nutrient losses from the Australian sheep meat value chain on Australian food and nutrition security, the authors explored the impact of the losses with respect to satisfying the nutritional needs of women of reproductive age. This subset of the population was chosen as they have a heightened demand for nutrients before and during pregnancy and lactation, and deficiencies of micronutrients can have intergenerational impacts; as such women of reproductive age are considered nutritionally vulnerable (Allen, 2005; Torheim and Arimond, 2013; Food and Agricultural Organization, 2021c). The World Health Organization (WHO) estimated 5.2–15.3% of Australian women of reproductive age were anemic in 2019 (World Health Organization, 2023) and that the prevalence of anemia in pregnant Australian women is 25% (World Health Organization, 2015). Carter et al. (2023) found the overall incidence of iron-deficiency anemia in pregnant women in far north Queensland in 2018 was 34.9%, with 48.7% of women identifying as Aboriginal or Torres Strait Islanders in the area experiencing iron-deficiency anemia during pregnancy.

2 Material and method

The Food Loss and Waste Accounting and Reporting Standard (FLWS) is a guidance document developed to facilitate countries (and other entities) to account for and report food loss and waste, including reporting against SDG12.3.1 (Food Loss and Waste Protocol, 2016). The FLWS states that each entity defines food loss depending on the reason for accounting and reporting the food loss (e.g., food security and nutrition, environmental assessment, economic assessment). The scope of the food loss is defined by material type (i.e., edible, inedible or both), destination or pathway of the materials, timeframe and boundaries of the food loss inventory (i.e., food category, life cycle stage and geography) (Food Loss and Waste Protocol, 2016). The FLWS allows for holistic accounting and reporting of food loss, as the unit of measure for food loss can range from nutrients to money, to environmental indicators such as water use and greenhouse gas emissions.

Nutrient losses (by weight) from the pre-consumer Australian sheep meat value chain were quantified, based on the FLWS (Food Loss and Waste Protocol, 2016) using the principles of a material flow analysis (Brunner and Rechberger, 2017).

2.1 Scope

The scope of the food loss accounting and reporting included timeframe, material type, destination and system boundaries (food category, lifecycle stage and geography), as per the FLWS (Food Loss and Waste Protocol, 2016).

2.1.1 Timeframe

The base year was calendar year 2015, and as per the Food loss and waste accounting and reporting standard, this was an average of calendar years 2014–2016 (Food Loss and Waste Protocol, 2016) where the data were available. Disease prevalence data from abattoir monitoring included data from calendar years 2010–2016, due to only having access to published data from Export Production and Condemnation Statistics (Lane et al., 2015) from July 2010 – June 2013. All other timeframes were as per the Food loss and waste accounting and reporting standard (Food Loss and Waste Protocol, 2016).

2.1.2 Material type

Food only products from the Australian sheep meat value chain were the material types quantified, expressed both in raw weight of products and, weight of nutrients in the raw, edible components of the products. Products were considered food if they were listed in the Australia New Zealand Food Standards Code – Standard 2.2.1 – Meat and meat products (Australian Government, 2016), Handbook of Australian Meat (AUSMEAT, 2020) or on the AUSNUT database (Food Standards Australia New Zealand, 2014).

Nutrients included in this study were those included in AUSNUT 2011–13 – Food nutrient database, except for nutrients imputed as zero (Food Standards Australia New Zealand, 2014). Only an estimate of the total nutrient was included in cases where numerous forms of the nutrient appeared in the database. For example, folate, natural, total folates, and dietary folate equivalents were represented by dietary folate equivalents in this study (Table 1). In the AUSNUT database, the carcase meat nutrient values were derived using a recipe approach, based on analyzed data and, the lamb offal nutrient composition data was analyzed. In this instance, the recipe approach for muscle meat was utilized as the cuts of meat were analyzed for gross composition, fatty acid profile and nutrient profile individually and then combined to create the food nutrient profile.

We assumed adult sheep offal had the same nutrient composition as lamb offal as the authors were unable to find any published data on the nutrient composition of Australian adult sheep offal. This is most likely a conservative estimate of nutrient composition of adult sheep offal, based on the differences between lamb meat and mutton meat i.e., micronutrient levels increased in muscle meat as animals aged

TABLE 1 Nutrients included in the food and nutrient loss assessment of the Australian sheep meat value chain.

Macronutrients	Vitamins	Minerals	Fats and others
Energy with dietary fiber	**Vitamin A retinol equivalents**	Calcium	Cholesterol
Moisture	**Thiamine (B1)**	Iodine	Total saturated fat
Protein	Riboflavin (B2)	**Iron**	Total monounsaturated fat
Ash	Niacin derived equivalents	Magnesium	Total polyunsaturated fat
Total fat	**Dietary folate equivalents**	Phosphorus	Linoleic acid
Tryptophan	Vitamin B6	Potassium	Alpha-linolenic acid
	Vitamin B12	Selenium	C20:5w3 Eicosapentaenoic
	Alpha-tocopherol	Sodium	C22:6w3 Docosahexaenoic
	Vitamin E	Zinc	Total long chain omega 3 fatty acids
			Total trans fatty acids

Nutrients in bold were considered significant to Australian public health.

(Williams et al., 2007) and that vitamin A concentrations increase in liver tissue as animals age (Majchrzak et al., 2006).

The authors were particularly interested in nutrients they considered to be significant to Australian public health. Criteria for nutrients to be classified as significant to public health in this study included:

- nutrients where a 100 g raw serve of any of the lamb or mutton carcase cuts or offal pieces supplies at least 20% of the recommended daily intake for Australian men and women (aged 19–50 years) is considered a good source for Australians (Australian Government, 2018) and the nutrient is either,
- monitored by the World Health Organization (WHO) (World Health Organization, 2020), or
- there is a mandate to fortify staple foods with the nutrient in Australia (Food Standards Australia New Zealand, 2019b).

2.1.3 Destination

A pathways approach was taken when determining the flow of food products and nutrients through the Australian sheep meat value chain, rather than the preferred destination approach. This meant the initial paths taken by the food product on their way to their destination, either downgraded or fit-for-human consumption, were considered as the two options The pathway approach was selected due to inadequate detail being included in published national data on the destination of products of the Australian sheep meat value chain. Food products and nutrients entered one of two pathways at the abattoirs, either fit for human consumption or unfit for human consumption (Figure 1).

2.1.4 Boundary

Four areas were considered in regards to the system boundaries of the food loss model – geography, organization, life cycle stage and, food category, as per the FLWS (Food Loss and Waste Protocol, 2016).

The geography was set to Australia, country code 036 (Statistics Division of the United Nations Secretariat, 2022). The organization was the sheep meat value chain. The sheep meat value chain was separated into lambs and adults to account for the variation in nutrient profile of the food products as animals age (Williams et al., 2007) and the variation in the prevalence of disease and contamination as animals age (Animal Health Australia, 2021).

One life cycle stage was selected, the abattoir (Figure 2). This is the point in the supply chain where animals are processed into food and other products (Figure 3). This stage was chosen as this is the first step where losses from animal-source value chains are accounted for in the FLWS (Food Loss and Waste Protocol, 2016).

Food categories included were those that had published Australian weight data (including edible portion information) and food composition data, noting the substitution of lamb offal nutrient composition data for adult sheep offal nutrient composition (Table 2). Based on the available data, from here on in this manuscript offal refers to liver, kidney, heart, tongue, and brain.

Raw liver, kidney and heart weights were taken from analyzed data in Sentance (2011). These weights were not disaggregated by age, so we assumed the weight for lamb and adult sheep offal was the same. Tongue and brain raw weights were taken from analyzed data in Hutchison et al. (1987); this data is for lambs only and we assumed that adult sheep had the same tongue and brain weights as lambs (Table 3).

2.2 Quantification of food and nutrient loss from the Australian sheep meat value chain at the abattoir in base year 2015

Food and nutrient losses from the Australian sheep meat value chain were estimated using inference by calculation. The FLW Quantification Method Ranking Tool (Food Loss and Waste Protocol, 2016) was used to select the method to achieve the aims stated in the Introduction. Mass Balance was the highest ranked methodology, scoring 90/100, and the only “green” category, i.e., based on our answers to the FLW Quantification Method Ranking Tool questionnaire, this was the only method recommended for further consideration.

The mass balance principle sequentially accounts for the weight of food and nutrients that arrived at the abattoir in animals ready for slaughter through to the weight of the edible portion of food and nutrients that were passed as fit for human consumption (Figure 4). This process was performed for the Australian lamb and the adult

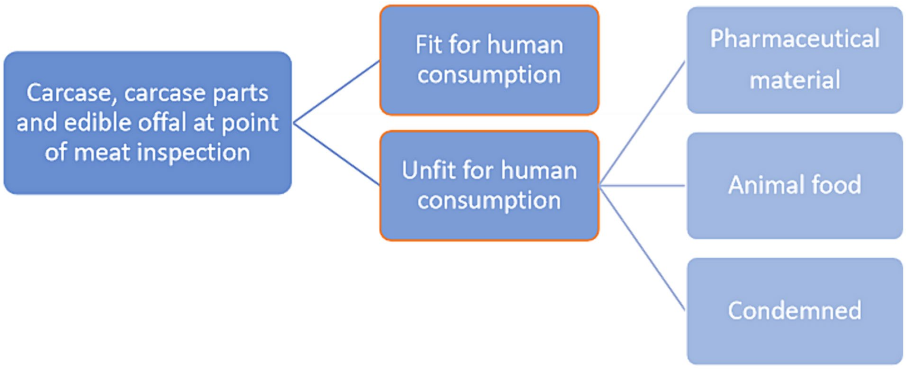

FIGURE 1
Destination of food products from the Australian sheep meat value chain at the abattoir. Boxes highlighted in orange represent the pathways included in this food and nutrient loss assessment.

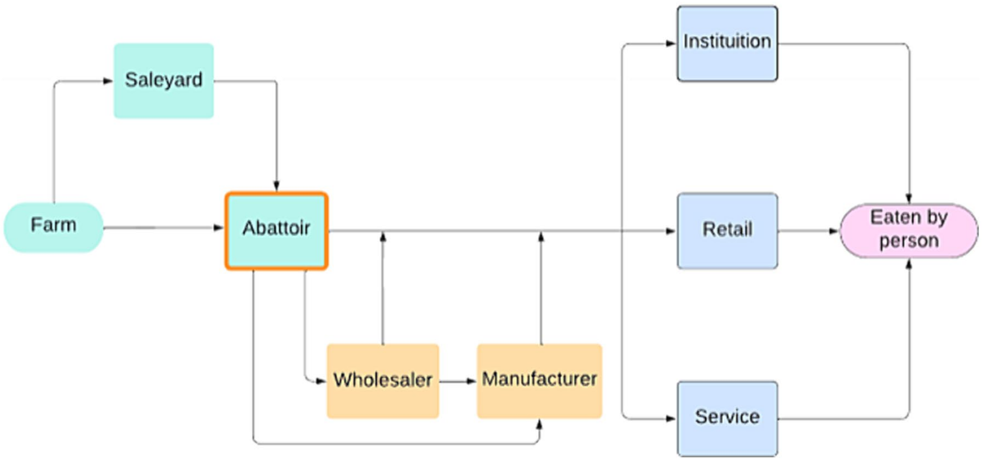

FIGURE 2
Australian sheep meat supply chain, highlighting the abattoir stage.

sheep meat (aka mutton) value chains. By combining the results of the Australian lamb and adult sheep value chains mass balance food and nutrient calculations, the combined food and nutrient flow for the Australian sheep meat value chain was determined.

Details on the calculations used to quantify ante-mortem and post-mortem direct nutrient losses from the Australian sheep meat value chain in 2015 are available in Appendix 1. The following is a summary of the steps taken and the data sources used in these calculations.

To begin with, the number of lamb and mutton carcases passed fit for human consumption was calculated from the dataset published by the Australian Bureau of Statistics, Livestock Products (Australian Bureau of Statistics, 2020b). Then, the ante-mortem and post-mortem populations were estimated, using these data and Export Production and Condemnation Statistics published in Lane et al. (2015).

Next, the prevalence of disease was calculated using data from the National Sheep Health Monitoring Project (Animal Health Australia, 2021) and the priority list of endemic diseases of the red meat industries (Lane et al., 2015). As a result, thirty (30) conditions were considered in this estimate of losses through the abattoir, with variation in what product was downgraded depending on the condition (Table 4). The weight of raw product downgraded due to these conditions was then calculated, based on analyzed data from Hernandez-Jover et al. (2013), Food Regulation Standing Committee (2007), expert elicitation and the prevalence calculations. Then, the weight of liver and kidneys condemned due to cadmium contamination was calculated based on the Meat Notice: Establishment sourcing of stock to comply with importing country requirements for cadmium levels in offals (Australian Government, 2015). The condemnation rate of offal due to cadmium contamination was adjusted to take into consideration condemnation due to disease. The edible nutrient losses were then calculated using the method described in Wingett and Alders (2023). The number of Australian women of reproductive age whose annual supply of red meat and key nutrients could have been supplied by the downgraded products and nutrients was then calculated, based on the Australian Dietary Guidelines (National Health and Medical Research Council, 2013) and the Australian and New Zealand Nutrient Reference Values (Australian Government and New Zealand Government, 2017).

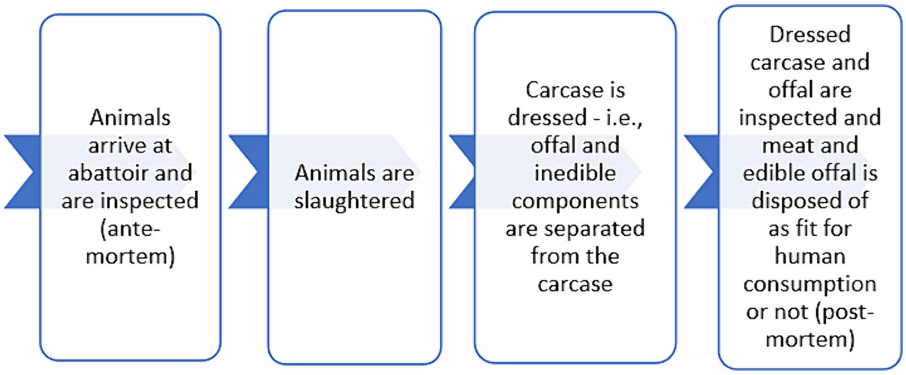

FIGURE 3
Processing flow at Australian sheep abattoirs.

As per the FLWS, an uncertainty assessment was performed on the results; a qualitative approach was taken to this assessment, based on the available data in the national datasets. Potential sources of uncertainty considered included systematic errors, assumptions, third-party data, model uncertainty and uncertainty in data used for inference (Food Loss and Waste Protocol, 2016).

3 Results

Overall, the Australian sheep meat value chain is very efficient at the processing stage, with generally low levels of food and nutrient losses, except for kidney and liver from the adult sheep value chain and, correspondingly, vitamin A RE and dietary folate equivalents. As expected, the lamb value chain was more efficient than the adult sheep value chain, with reduced levels of food loss by product and nutrient weight.

This mass balance analysis had an overall qualitative uncertainty assessment of medium-to-high. It is important to consider this when interpreting the results.

3.1 Sheep population in base year 2015

In 2015, 22.69 million lamb and 8.51 million mutton carcases were passed as fit for human consumption. Approximately 99.92% of lambs that arrived at the abattoir passed ante-mortem inspection and had their carcases passed as fit for human consumption at post-mortem inspection. Of the 0.08% of the lamb population that had full carcase condemnations, the majority occurred at post-mortem inspection, i.e., 99.04% of full carcase condemnations occurred at post-mortem inspection. Approximately 99.32% of adult sheep that arrived at the abattoir passed ante-mortem inspection and had their carcases passed as fit for human consumption at post-mortem inspection. Of the 0.68% of the adult sheep population that had full carcase condemnations, the majority occurred at post-mortem inspection, i.e., 98.59% of the full carcase condemnations occurred at post-mortem inspection.

The ante-mortem populations for the lamb and adult sheep value chains were calculated to be 22.71 million and 8.57 million, respectively.

3.2 Raw weight of product losses in base year 2015

Ante-mortem condemnations were considered a "condition" for the remainder of the analysis, due to their relatively small prevalence compared with post-mortem downgrades, for both carcases/carcase parts and offal pieces.

Less than 1% of carcase meat, kidney, heart, tongue, and brain being downgraded as not-fit-for human consumption. There were mildly elevated losses of lamb liver, with approximately 2% downgraded (Table 5).

The adult sheep value chain had a greater proportion of losses compared with the lamb value chain for all products. Product losses ranged from <1% (brain) to 96% (kidney) (Table 5). Adult sheep losses for carcase, heart, tongue, and brain were three-to-four-fold those for lamb. Losses for liver and kidney were markedly increased in the adult sheep chain compared with the lamb chain; approximately 26 times greater for liver and more the 1900 times greater for kidney.

Product losses of the adult sheep value chain were buffered by losses in the lamb value chain when the products for both value chains were combined (Table 5). This was due to there being a greater proportion of lambs being slaughtered in 2015 compared with adult sheep; for every adult sheep slaughtered approximately 2.5 lambs were slaughtered. Losses from the adult sheep value chain still formed a significant proportion of total carcase and edible offal pieces. Adult sheep kidney downgrades accounted for more than 99% of combined kidney losses (noting that nephritis was not included in the National Sheep Health Monitoring Project in 2015), 91% of combined liver downgrades, 70% of combined carcase downgrades, 60% of heart and tongue downgrades and, 59% of combined brain downgrades.

Total product losses from the Australian sheep meat value chain ranged from <1% of brains to 26% of kidneys. Less than 1% of carcase meat, heart, tongue, and brain were downgraded from the Australian sheep meat value chain during processing at the abattoir during 2015. Approximately 17% of livers and 26% of kidneys were downgraded as not-fit-for-for human-consumption from the combined Australian sheep meat value chain during the same period (Table 5).

Based on the maximum intake of red meat in the Australian Dietary Guidelines (National Health and Medical Research Council, 2013), and the assumption that a healthy intake of offal is the same as that as carcase meat, the annual product losses from the combined

TABLE 2 Food categories included in the mass balance calculation of food and nutrient losses from the Australian sheep meat value.

Food name	AUSNUT* 2011–13 food id	HAM^ number	CPC+	ANZSIC# (Division and class)
Lamb, easy carve shoulder, untrimmed, raw	08A20691	4,990	21,115	C/1111
Lamb, forequarter chop, untrimmed, raw	08A20700	5,020	21,115	C/1111
Lamb, shank, untrimmed, raw	08A20679	5,030	21,115	C/1111
Lamb, diced, untrimmed, raw	08A20673	5,010	21,115	C/1111
Lamb, frenched cutlet/rack, untrimmed, raw	08A20707	4,930	21,115	C/1111
Lamb, loin chop, untrimmed, raw	08A20721	4,880	21,115	C/1111
Lamb, leg roast, untrimmed, raw	08A20714	4,830	21,115	C/1111
Lamb, chump chop, untrimmed, raw	08A20667	4,790	21,115	C/1111
Mutton, shoulder, untrimmed, raw	08A20753	4,992	21,115	C/1111
Mutton, leg roast, untrimmed raw	08A20791	4,830	21,115	C/1111
Lamb, tongue, raw	08D10183	7,010	21,155	C/1111
Lamb, liver, raw	08D10185	7,030	21,155	C/1111
Lamb, kidney, raw	08D10181	7,040	21,155	C/1111
Lamb, brain, raw	08D10177	7,070	21,155	C/1111

Sources: AUSMEAT, 2020, Department of Economic and Social Affairs (2015), Food Standards Australia New Zealand (2014), and Australian Bureau of Statistics (2013a). *AUSNUT 2011–13: is a food composition database developed to enable food, dietary supplement and nutrient intake estimates to be made from the 2011–13 Australian Health Survey. ^HAM: Handbook of Australian Meat is an international red meat guide used to facilitate the use of accurate product descriptions in domestic and international trade. +CPC: Central Product Classification is a complete product classification covering all goods and services. #ANZSIC: Australia and New Zealand Standard Industrial Classification.

Australian sheep meat value chain could provide approximately 310,000 adult Australians with all their red meat for the year.

3.3 Losses of nutrients key to public health available in base year 2015

As for product losses, there were proportionally more losses of nutrients key to public health from the adult sheep value chain than the lamb value chain. Nutrient losses from the lamb value chain ranged from <1% of thiamine (B1), iron, energy, and protein to 2% of dietary folate equivalents and vitamin A RE. The range of nutrient losses was greater for the adult sheep value chain (4% of energy to 57% vitamin A RE) but followed the same pattern as the lamb value chain. Again, nutrient losses from the Australian sheep meat value chain were skewed toward the lamb value chain, ranging from 1% of energy to 17% of vitamin A RE (Table 6).

The number of Australian women of reproductive age whose annual nutrient requirements could have been met with the downgraded products ranged from 66,000 for thiamine (B1) to 6.6 million for vitamin A RE. This calculation was based on the estimated average requirement for Australian women aged 19–50 years (National Health and Medical Research Council, 2013).

3.4 Causes of product and nutrient losses in base year 2015

In this section, the relative contributions of various conditions to the total product downgrades and quantity of nutrient losses at the abattoir in the base year 2015 were analyzed. The Australian lamb and adult sheep value chains were individually assessed, and their combined impact was considered.

The leading causes of lamb and mutton carcase downgrades were identified as arthritis (34%) and caseous lymphadenitis (CLA) (28%). In the combined Australian sheep meat value chain, arthritis continued to be the primary cause (23%), followed by CLA (21%). For specific organs, bladder worm (89%) and cadmium contamination (79%) emerged as the primary causes of downgraded lamb and adult sheep livers (Figure 5).

The study then estimated the relative contribution of each condition to the total amount of key nutrients downgraded. Cadmium contamination was consistently identified as a significant contributor, accounting for more than 50% of downgrades for vitamin A RE, thiamine (B1), dietary folate equivalents, and iron. When bladder worm was included, this percentage increased to over 70% (Figure 6). The causes of energy and protein losses were less concentrated than for micronutrients. However, cadmium and bladder worm still accounted for a substantial portion, contributing to 42 and 51% of downgraded energy and protein, respectively, in the combined Australian sheep meat value chain (Figure 6).

There were 11 conditions that contributed to less than 1% loss of any products and any nutrient from the lamb, adult sheep, or combined value chain. These conditions were anemia, bruising, dog bite, ecchymosis, hydatids, gangrene, muscle conditions, metritis, other causes, peritonitis, and wounds.

3.5 Uncertainties in the assessment of food and nutrient loss from the Australian sheep meat value chain

Uncertainties in the calculation of food and nutrient loss from the Australian sheep meat value chain were qualitatively rated on a five-point scale - very low, low, medium, high, very high – and a justification for the rating provided (Table 7). This method was

TABLE 3 Raw offal weights.

Raw offal piece	Weight (kg)
Liver	0.707
Kidney (x2)	0.149
Heart	0.251
Tongue	0.0955
Brain	0.093

Sources: Hutchison et al. (1987) and Sentance (2011).

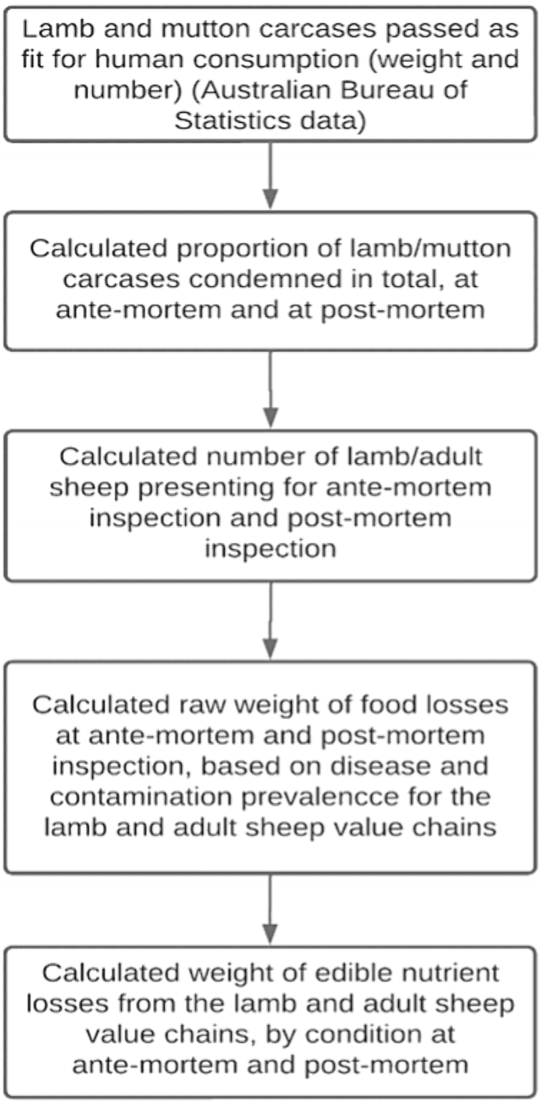

FIGURE 4
Framework for calculating the food and nutrient losses from the abattoir stage of the Australian lamb and adult sheep value chains.

selected as the Food Loos Waste Accounting and Reporting Standard recommends including a qualitative uncertainty assessment of the assessment as a minimum (Food Loss and Waste Protocol, 2016).

Factors taken into consideration in rating uncertainties included:

- the age of the data,
- type of data (analyzed, survey, recipe, secondary),
- the number of samples in the original data set, and
- data availability statement

Averaging the sub-total ratings, overall, the uncertainty in this mass balance analysis is medium-to-high.

4 Discussion

The result suggest that the Australian lamb value chain had minimal losses of both products and nutrients during processing in 2015 (Tables 5, 6). Downgrades affected less than 1% of all pre-slaughter products, except for liver, with a 2% downgrade rate. These results are consistent with the findings in the National Food Waste Baseline Assessment (ARCADIS, 2019). Nutrient downgrades were also less than 1% for thiamine (B1), iron, energy, and protein, but vitamin A RE and dietary folate equivalents each having 2% downgrade. On the other hand, the adult sheep value chain had low downgrades for most products, but major downgrades for liver (58%) and kidneys (96%) due to cadmium contamination, resulting in substantial losses of vitamin A RE (57%), dietary folate equivalents (39%), iron (10%), thiamine (B1) (8%), protein (5%), and energy (4%). Combining both value chains, nutrient and energy downgrades from products ranged from 1% for energy to 17% for vitamin A RE.

Bladder worm (89%) and cadmium contamination (79%) were the main causes of downgraded lamb and adult sheep livers, respectively. Conditions causing lamb kidney downgrades were directly related to conditions causing full carcase and offal condemns, however adult sheep kidney downgrades were dominated by cadmium contamination (100%). The top five conditions for downgrades of heart, brain and tongue across the lamb and adult sheep value chains were reflective of the top five conditions causing full carcase and offal condemnations.

The medium to-high uncertainty in the food and nutrient loss calculations have arisen mostly due to assumptions that were made in cases where there was no data. These assumptions were generally conservative in nature and as such, the losses may be underestimated. The level of uncertainty highlights published data gaps in production volumes, destination, and nutrient composition of Australian sheep meat product, particularly of edible offal.

The losses of micronutrients key to public health in Australia reflect the disproportionate losses of edible offal from the Australian sheep meat value chain compared with carcase products, in particular liver and kidney. On a per gram basis, liver and kidney have a greater concentration of all micronutrients key to public health than carcase meat (Food Standards Australia New Zealand, 2014). In an individual lamb, liver absolutely contains greater amounts of vitamin A RE and dietary folate equivalents than the carcase, kidneys, heart, tongue and brain combined (Wingett and Alders, 2023). Cadmium contamination of liver and kidney in adult Australian sheep was the leading cause of losses of all nutrients key to Australian public health and energy. There are maximum cadmium levels in mammalian offal set in the Food Standards Australia and New Zealand and in export markets (Australian Government, 2020b). Based on the maximum levels of cadmium allowed in Australia in 2015, kidneys from adult sheep from all Australian states, except Queensland, were downgraded as not fit for human consumption. Livers from adult sheep from three states

TABLE 4 **Carcase and offal downgrades by condition used in the mass balance calculation of food and nutrient losses from the Australian sheep meat value chain at the abattoir.**

Condition	Carcase	Liver	Kidney	Heart	Tongue	Brain
Arthritis	✕ (red)	✓	✓	✓	✓	✓
Caseous lymphadenitis	✕ (red)	✕ (purple)	✕ (purple)	✕ (purple)	✕ (purple)	✕ (purple)
Dog bite	✕ (red)	✓	✓	✓	✓	✓
Grass seed	✕ (red)	✓	✓	✓	✓	✓
Sheep measles	✕ (red)	✕ (purple)	✕ (purple)	✕ (purple)	✕ (purple)	✕ (purple)
Pleurisy	✕ (red)	✓	✓	✓	✓	✓
Sarcocystosis	✕ (red)	✓	✓	✕ (purple)	✕ (purple)	✓
Vaccination lesion	✕ (red)	✓	✓	✓	✓	✓
Bladder worm	✓	✕ (red)	✓	✓	✓	✓
Hydatids	✕ (purple)	✕ (red)	✕ (purple)	✕ (purple)	✕ (purple)	✕ (purple)
Liver fluke	✓	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)
Anemia	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)
Bruising	✕ (red)	✓	✓	✓	✓	✓
Company condemns	✕ (red)	✓	✓	✓	✓	✓
Ecchymosis	✕ (red)	✓	✓	✓	✓	✓
Emaciation	✕ (red)	✓	✓	✓	✓	✓
Fever	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)
Gangrene	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)
Gross contamination	✕ (red)	✓	✓	✓	✓	✓
Jaundice	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)
Malignancy	✕ (red)	✓	✓	✓	✓	✓
Metritis	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)
Muscle condition	✕ (red)	✓	✓	✓	✓	✓
Other causes full carcase condemns	✕ (red)	✓	✓	✓	✓	✓
Peritonitis	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)
Pyaemia	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)
Septic pneumonia	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)
Wounds	✕ (red)	✓	✓	✓	✓	✓
Ante-mortem	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)	✕ (red)
Cadmium	✓	✕ (red)	✕ (red)	✓	✓	✓

Red cross (✕) indicate the food product was accounted for as downgraded whenever the condition was present, regardless of whether the carcase was condemned or trimmed. Purple cross (✕) indicate the product was only accounted for as downgraded whenever the condition was present, and the carcase was condemned. Green tick (✓) indicate the food product was accounted for as fit-for-human consumption when the animal had the condition.

were also downgraded due to cadmium contamination (Western Australia, South Australia and Victoria), with restricted export markets for the remaining three states (Tasmania, New South Wales and Queensland) (Australian Government, 2015).

In 2020, a new Meat Notice - Establishment sourcing of stock to comply with import country requirements for cadmium levels in offal – was published Australian Government (2020b). This set policy for the management of cadmium levels in liver and kidney from adult sheep and cattle based on sub-regions of states, rather than at the state level (Australian Government, 2020a).Applying the conditions in this new Meat Notice to the 2015 food loss estimation, the percentage of kidneys eligible for harvest from adult sheep would have increased from 4 to 27% and for liver from 45 to 47%. Subsequently, there would have been a 3% increase in dietary folate equivalent availability and a 5% increase in Vitamin A availability.

Soil cadmium is transferred to livestock via ingestion of plants and soil. Cadmium then bioaccumulates in the kidneys and liver. Soils can be contaminated with cadmium through application of rock phosphate fertilizers, sewage sludge and industrial wastes (Ismael et al., 2018; Australian Government, 2022; Mubeen et al., 2023). Australian soils have low levels of natural cadmium and fertilizer application is the most significant contributing source of the cadmium to the Australian sheep meat value chain (Warne et al., 2007; MacLachlan et al., 2016).

TABLE 5 Percentage of products downgraded at the abattoir in base year 2015, relative to the amount of product available from animals presented for ante-mortem inspection in the Australian lamb-, adult sheep- and combined sheep meat value chains.

Product	Lamb value chain loss as % total available at ante-mortem	Adult sheep value chain loss as % of total available at ante-mortem	Combined value chain loss as % of total available at ante-mortem	Number of Australian adults whose red meat intake could have been met with the combined losses
Carcase	<1	2	<1	170,099
Liver	2	58	17	105,815
Kidney	<1	96	26	33,856
Heart	<1	<1	<1	185
Tongue	<1	<1	<1	70
Brain	<1	<1	<1	66

TABLE 6 Losses of nutrients key to public health at the point of slaughter, as a percent of total available at ante-mortem from the Australian lamb, adult sheep, and combined value chains in base year 2015.

Nutrient	Lamb value chain loss as % total available at ante-mortem	Adult sheep value chain loss as % of total available at ante-mortem	Combined value chain loss as % of total available at ante-mortem	Number of women of reproductive age whose annual nutrient requirements could have been met with the combined losses
Vitamin A retinol equivalents	2	57	17	6.6 million
Thiamine (B1)	<1	8	3	66,000
Dietary folate equivalents	2	39	12	261,000
Iron	<1	10	4	211,000
Energy	<1	4	1	n/a
Protein	<1	5	2	145,000

The number of Australian women of reproductive age (19–50 years) whose nutrient requirement could have been met with the nutrients lost from the combined Australian sheep meat value chain losses in the base year was calculated, based on estimated average requirements.

In Australia, the level of cadmium in fertilizers is regulated by the jurisdictions and is set at 300 mg cadmium per kilogram of phosphorus. With growing interest in circular bioeconomies, cadmium levels in organic fertilizers and soil amendments, such as biosolids, also needs to be managed to minimize the risk of further increasing soil cadmium in agricultural areas, particularly where rock phosphate fertilizers have been previously applied (Alders et al., 2021; Fertilizer Australia, 2024). This may include regulation of cadmium levels in these products, much as rock phosphate fertilizers are regulated (NSW Government, 2014).

The authors recommend that when the regulated level of cadmium in fertilizer and organic soil amendments is next reviewed, the impact of cadmium on liver and kidney downgrades and nutrient availability is taken into consideration. Gains in reducing food and nutrient loss have been made with the change of the Meat Notice (Australian Government, 2020b); reducing regulated cadmium limits in fertilizers and soil amendments also has the potential to positively influence nutrient availability.

The prevalence of cadmium contaminated kidneys and livers in the Australian sheep meat value chain was determined via calculation, taking into consideration the age and location of the sheep and the Meat Notice on cadmium disposition (Australian Government, 2015). This was due to there being no published data on the prevalence of cadmium contamination of sheep liver and kidneys. Consideration should be given to including cadmium downgrades in the National Sheep Health Monitoring Project to gain a more accurate understand of the scale of the impact of cadmium contamination on nutrient availability from the Australian sheep meat value chain.

Bladder worm was the second highest ranked condition responsible for downgrades of nutrients key to Australian public health from the Australian sheep meat value chain. This condition is caused by the dog tapeworm, *Taenia hydatigena*. Sheep become infected from eating tapeworm eggs that an infected dog has passed in its faces; dogs become infected by eating infected raw offal or scavenging on infected carcases (Animal Health Australia, 2021). The prevalence of the condition can be significantly reduced through regular de-worming of dogs, prompt disposal of any fallen stock to reduce scavenging, not feeding dogs raw offal and, wild dog and fox control. Mitigations for bladder worm will also be effective for controlling sheep measles and hydatids (Animal Health Australia, 2021; Shephard et al., 2022). The condition is not clinically evident in live sheep or dogs. This means sheep producers will only be aware they have the condition in their flock when feedback from the abattoir is provided. Currently, this occurs in Australia for producers that sell sheep directly to slaughter at one of the 10 Australian abattoirs participating in the National Sheep Health Monitoring Project (Animal Health Australia, 2021). Consideration should be given to reorientating this monitoring project to a surveillance program,

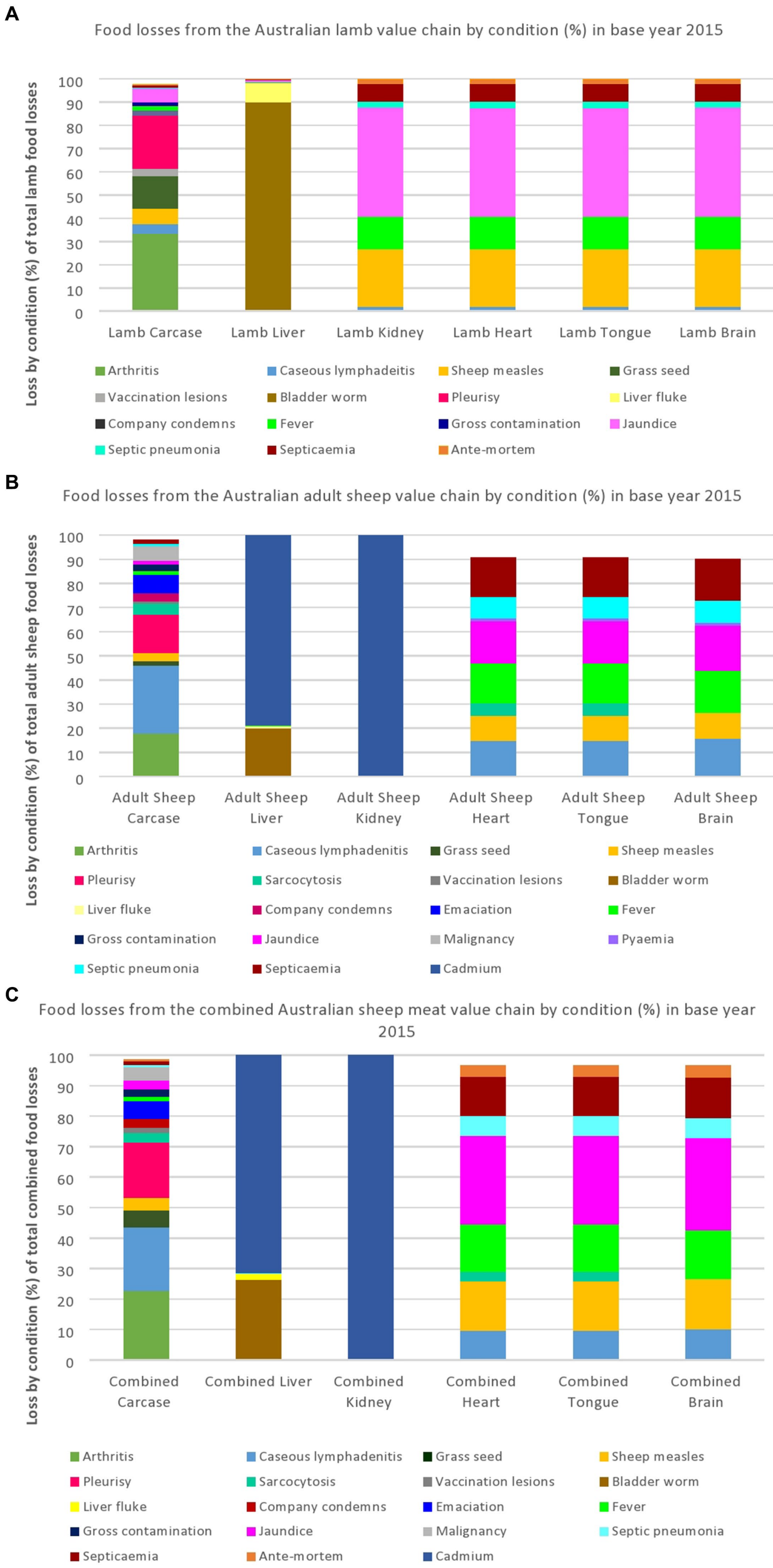

FIGURE 5
Cause of losses at the abattoir from the Australian lamb **(A)**, adult sheep **(B)** and combined **(C)** value chains in base year 2015, represented as a proportion of total losses of products by weight. Some categories do not total to 1.0 as losses from conditions that accounted for less than 1% of the total losses of each product were not included. CLA, caseous lymphadenitis.

including expanding feedback to all producers, regardless of sale method. This is based on the contribution bladder worm infection has on nutrient availability from the Australian sheep meat value chain.

Neither cadmium or bladder worm were included in the report from Shephard et al. (2022) on priority endemic diseases for the Australian sheep and cattle industries. This report ranked conditions on economic impact the conditions had on the industries. Consideration should be given to ranking conditions not only on economic impact, but also the impact the condition has on food and nutrient availability at the society level. This will assist when assessing the Australian sheep meat value chain's contribution to food security and natural resource management (if the assessment is using nutrients as the functional unit).

Improvements in data availability and quality would increase the accuracy of quantifying food and nutrient losses from the Australian sheep meat value chain. Issues with data quality affecting food loss and waste assessments are well documented (Food and Agricultural Organization, 2011; Xue et al., 2017; Hoehn et al., 2023). The FAO's Global Livestock Environmental Assessment Model, known as GLEAM, aims "to quantify production and use of natural resources in the livestock sector and to identify environmental impacts of livestock in order to contribute to the assessment of adaptation and mitigation scenarios to move toward a more sustainable livestock sector" (Food and Agricultural Organization, 2021b). GLEAM currently does not include offal in its calculations. This is due to the lack of reported information from any of its member states on offal production globally (Food and Agricultural Organization, 2022). The impact of this on assessing the sustainability of livestock systems is marked, not only from a nutritional perspective as the results of this food loss assessment have shown, but also from a natural resource management perspective.

Wiedemann and Yan (2014) found that by including edible offal in the functional unit when calculating greenhouse gas emissions, the liveweight required on farm for each kilogram of retail product was reduced by 12%. Wingett and Alders (2023) conservatively estimated edible offal accounted for 12% of the total weight of edible components, 10% of the edible protein and 5% of edible energy of an Australian lamb. Not including edible offal when assessing the costs and benefits of livestock systems will over-estimate the relative impact of animals on the natural environment and underestimate the nutrient availability from livestock systems. This is particularly evident when performing nutritional life cycle assessment (McAuliffe et al., 2018; Damerau et al., 2019). Cases of successful reduction of food loss and waste are reported to have had strong government support (Kuiper and Cui, 2021). Developing commercially viable systems to capture offal production data and downgrades (including cause and magnitude) should be a priority for both the meat industries and governments.

Greater transparency in agricultural data sharing would improve the accuracy in this food loss assessment. The inclusion of full carcase condemnations in the Livestock Products, Australia series published by the Australian Bureau of Statistics would assist with this process. This information is captured in the equivalent national statistical series in New Zealand (Statistics New Zealand, 2021). The rate of full condemnations is comparable between the two countries, and both are low, with less than 1/100 adult sheep being condemned and less than 1/1000 lambs being condemned. This shows the high standard of the Australian and New Zealand sheep meat production and could be used as an indicator for animal health and welfare at the national level for the industry. Publication of data on the number of animals, disaggregated by species, age and sex, that are processed at knackeries (establishments that slaughter animals for animal food only) would also be of benefit to understanding the magnitude of product and nutrient losses from Australian livestock systems, as well as gaining a fuller understanding of animal health and welfare.

Further consideration needs to be given to the assumption in the 'State of Food and Agriculture 2019 – Moving forward on food loss and waste reduction' report (Food and Agricultural Organization, 2019), Global food loss index accounting and reporting (Food and Agricultural Organization, 2018) and the Australian national food waste baseline (ARCADIS, 2019) that a product that was intended to be food (e.g., edible offal) but is diverted to another supply chain (e.g., monogastric animal feed) and later enters the food chain in another form (e.g., chicken or pork) is a neutral outcome from a food systems perspective. The results of this mass balance analysis show that the downgrade of offal is a significant contributor to the downgrade of nutrients from the Australian sheep meat value chain. Australians eat very little nutrient-dense offal, less than 0.4 g per person per day, compared with 48.4 g of red meat and 48.7 g of poultry meat (Australian Bureau of Statistics, 2022a). However, a serve of chicken breast is not equal nutritionally to a serve of lamb liver. Although chicken breast has similar fat, protein and energy content to lambs' liver, liver has significantly greater concentrations of micronutrients key to Australian public health, i.e., iron, vitamin A RE, thiamine (B1) and dietary folate equivalents. Additionally, there is an environmental impact from raising chickens (e.g., soybean meal being imported from South America as a feed input for the Australian chicken meat industry (Copley and Wiedemann, 2023)) that would not have occurred if the lamb and sheep offal had entered the food chain directly, rather than through nutrient recycling. Further research is recommended to understand the end points of products in Australian sheep meat value chain and the consequences of this nutrient recycling. This is supported by recommendations in the National Food Waste Baseline Final Assessment Report for further research into diversion of livestock products into the pet food supply chain (ARCADIS, 2019).

Based on the results of this food loss analysis, the Australian sheep meat value chain is very efficient at conserving food products and nutrients at the point of slaughter, except for kidney and liver condemnation due to cadmium contamination and the subsequent loss of dietary folate equivalents and vitamin A RE. However, these results have an overall uncertainty rating of medium-to-high. Greater transparency in agricultural data sharing would reduce this uncertainty. Further research into improved data collection on offal production and updating and expanding offal nutrient composition data will significantly improve the accuracy of this food and nutrient loss analysis. Quantifying pre-consumer waste of offal (e.g., offal fit for human consumption that is diverted to pet food or rendering due to market influences) will be of value in further understanding nutrient flows in the Australian sheep meat value chain and the impacts on food security, nutrition, and the environment. Government support for these actions will improve the likelihood of success and subsequently the sustainability of the Australian sheep meat value chain.

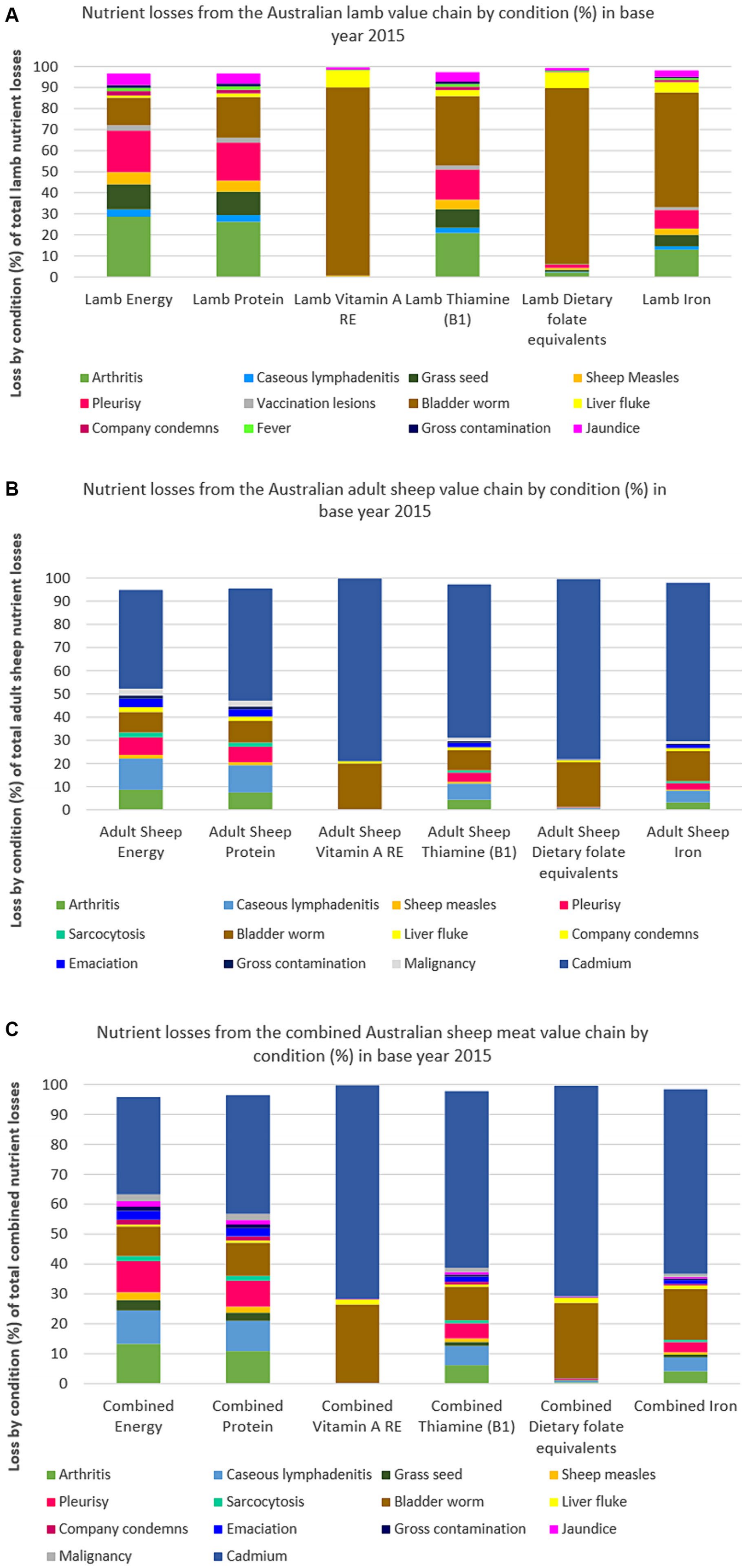

FIGURE 6
Cause of nutrient losses at the abattoir from the Australian lamb **(A)**, adult sheep **(B)** and combined **(C)** value chains in base year 2015, represented as a proportion of total losses of nutrients from the lamb value chain. Some categories do not total to 1.0 as losses from conditions that accounted for less than 1% of the total losses of each nutrient were not included. CLA, caseous lymphadenitis.

TABLE 7 Uncertainties in calculating food and nutrient losses from the Australian sheep meat value chain for base year 2015.

Source of uncertainty		Rating		Justification
Population	Number of lambs and adult sheep slaughtered, and carcases passed as fit for human consumption	Very low	Sub-total uncertainty rating for population: Low-to-medium	Data used is from surveys undertaken by the Australian Bureau of Statistics and reported to have good national coverage (Australian Bureau of Statistics, 2020a) There is no published Australian data on the number of animals processed at knackeries
	Full carcase condemnation rates	High		Based on secondary data published in Lane et al. (2015) from 2011 to 2013 and collected only from export – registered processing plants not in the timeframe required to establish a base year level
	Weight of carcases available ante-mortem and post-mortem	Very high		Calculated values based on data that has high uncertainty
	Weight of carcase available fit-for-human consumption	Very low		Data used is from surveys undertaken by the Australian Bureau of Statistics and reported to have good national coverage (Australian Bureau of Statistics, 2020a)
Prevalence of diseases/ conditions that cause downgrade of food products	Diseases/conditions included that cause downgrading of carcases and/or offal	High	Sub-total uncertainty rating for prevalence of disease/conditions: Medium-to-high	Due to no published data being available on nutrient composition of lung and gut, the conditions of lungworm, pneumonia and knotty gut monitored as part of the National Sheep Health Monitoring Project were not included in the assessment of food and nutrient losses from the Australian Sheep Meat Value Chain Not all conditions that cause downgrades are monitored in the National Sheep Health Monitoring Project Export Production and Condemnation Statistics Database does not capture domestic abattoirs or knackeries
	Disease prevalence causing trimming and/ or condemnation of carcases and offal	Medium		Researchers were provided access to the national sheep health monitoring project data (Animal Health Australia, 2021). This data is collected on a continuous basis in sheep processing plants across Australia. Export Production and Condemnation Statistics data is secondary data from 2011–2013 and does not include domestic abattoirs Animals that are processed at knackeries are not captured by National Sheep Health Monitoring Project or Export Production and Condemnation Statistics Prevalence of downgrades due to cadmium based on incomplete secondary data, with assumptions made on activities in domestic abattoirs, based on regulation of export registered abattoirs (Australian Government, 2015)

(Continued)

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TABLE 7 (Continued)

Source of uncertainty		Rating		Justification
Weight of food products downgraded	Weight of downgraded carcase meat per condition	Medium	Sub-total uncertainty rating for weight of product downgraded: High	Analyzed data used (Hernandez-Jover et al., 2013). This data was collected from one processing plant over a period of 6 months.
	Number of offal edible offal pieces passed as fit for human consumption	Very high		Calculated values based on data that has high uncertainty as no published data on total offal production in Australia.
	Offal condemnation rates	Very high		Calculated values based on data that has high uncertainty as no published data on offal condemnation rates in Australia
	Offal weights	Medium		Data is based on measurement, but is not disaggregated by age (Sentance, 2011) or is only for lamb (Hutchison et al., 1987) and both data sets are more than ten years old No published data available for thymus, lungs, blood, head meat, runners, caul fat and kidney fat
	Edible parts of lamb carcase conversion factor	Medium		Data is based on measurement and sample numbers of ten or less and data published more than ten years ago (Food Standards Australia New Zealand, 2019a)
	Edible parts of mutton carcase conversion factor	High		Very limited published data on gross composition of mutton cuts and/or carcase so assumed composition was the same for mutton as lamb (Food Standards Australia New Zealand, 2019a)
	Edible parts of offal pieces conversion factors	High		Data is more than 35 years old (Hutchison et al., 1987).
Nutrient composition of downgraded food product	Nutrient composition of lamb carcase meat	Medium	Sub-total uncertainty rating for nutrient composition of downgraded product: High	AUSNUT data used – this is a combination of analyzed and recipe data (Food Standards Australia New Zealand, 2014). Data is based on ten or less analyzed samples and is more than ten years old
	Nutrient composition of mutton carcase meat	High		Based on average of values of two cuts of mutton included in AUSNUT database (Food Standards Australia New Zealand, 2014). This data is based on ten or less analyzed samples and is more than ten years old.
	Nutrient composition of lamb offal	High		AUSNUT data used – this is analyzed data (Food Standards Australia New Zealand, 2014). Due to the age of this data, it is no longer included in the current Australian Food Composition Data (Food Standards Australia New Zealand, 2019a). No published Australian data available for thymus, lung, spleen, blood, head meat, stomach and intestines, caul fat and kidney fat
	Nutrient composition of adult sheep offal	Very high		Assumption the nutrient composition of adult sheep offal was the same as lamb offal, as there is no published data on the nutrient composition of any offal from adult Australian sheep

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Some of the data anaylzed in this study was obtained from Animal Health Australia and the following restrictions apply – data from the National Sheep Health Monitoring Project is only available to the researchers. Requests to access National Sheep Health Monitoring Project datasets should be directed to: aha@animalhealthaustralia.com.au. Generated datasets are available on request. The generated raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KW: Conceptualization, Data curation, Methodology, Writing – original draft. RA: Conceptualization, Writing – review & editing.

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Conflict of interest

KW declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. RA declares a potential conflict of interest in that she owns a merino sheep farm (which is not her primary source of income), however, her farm does not produce prime lambs.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1304275/full#supplementary-material

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Som Dutt,
Central Potato Research Institute (ICAR), India

REVIEWED BY
Marina Mefleh,
American University of Rome, Italy
Claudia Terezia Socol,
University of Oradea, Romania

*CORRESPONDENCE
Shreyasi Majumdar
s.majumdar@massey.ac.nz

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An nLCA approach to support consumer meal decisions: a New Zealand case study of toppings on toast

Shreyasi Majumdar[1]*, Sarah J. McLaren[1], Jolieke C. van der Pols[2] and Carolyn E. Lister[3]

[1]New Zealand Life Cycle Management (NZLCM) Centre, Massey University, Palmerston North, New Zealand, [2]School of Exercise and Nutrition Sciences, Faculty of Health, and Centre for Agriculture and the Bioeconomy, Queensland University of Technology, Brisbane, QLD, Australia, [3]The New Zealand Institute for Plant and Food Research Ltd, Lincoln, New Zealand

Introduction: This study investigates the development and potential application of a nutritional Life Cycle Assessment (nLCA) method to rank meals, using a case study of a "toppings on toast" (ToTs) meal. Methodological issues are investigated in the context of application to support consumers to make more informed food choices at the meal level.

Methods: Fourteen selected "toppings on toast" (ToTs) commonly consumed in New Zealand (NZ) were evaluated for their climate change impacts and nutritional value using the serve size of each topping as the functional unit (FU). NZ-specific climate change values were obtained from an existing database and recent literature. Nutritional value was calculated using the NRF family of indices – specifically the $NRF_{9.3}$ and $NRF_{28.3}$ indices (the latter constructed for this study to include all nutrients in the selected toppings for which reference values were available) and presented in a separate midpoint nutrition impact category. The NRF and climate change scores were assigned quartile-based weights, and the weight of each index score was averaged with that of the climate change score. Based on these average values, the toppings were ranked in two ranking sets (one for each index). In a sensitivity analysis, two alternative reference units were also used (100 g and 100 kcal) to investigate how different FUs influenced the final rankings.

Results: The results showed that use of one or other NRF index affected the magnitude of the nLCA results; however, the rankings of the ToTs based on the nLCA results did not change much between the two indices. Avocado and peanut butter performed the best (top two ranks), and bacon, butter, and cheese were the poorest performers (bottom two ranks), for both the ranking sets. The toppings which did change ranks mostly moved up or down by only one position. Thus, the results of this case study suggest that the $NRF_{9.3}$ index is sufficient to determine overall the best, medium, and worst performing toppings in the ToT meal context. However, the results also showed that water-soluble vitamins and unsaturated fats included in the $NRF_{28.3}$ index contributed significantly to the nutritional scores for most of the toppings and were instrumental in the rank changes for the toppings which are particularly rich in these nutrients.

Discussion: Thus, for a more diverse range of toppings/meals, an expanded index including these nutrients can generate more nuanced rankings. This study contributes to the nascent but fast-growing nLCA research field, particularly within the meal context. The method used in this case study could be applied in food composition databases, restaurant menus, and websites/apps that provides recipes for meals. However, the study also highlighted the potentially significant variability in climate change and nutritional values in the toppings associated with different production practices, seasonality, and different varieties of the same product. Any future development of nLCA-based meal level rankings should address this variability and communicate it to the consumer.

KEYWORDS

nLCA, life cycle assessment, nutrition, climate change, meals

1 Introduction

Agri-food systems have far-reaching environmental impacts, including significant contributions to climate change, biodiversity loss, freshwater use and pollution, and soil degradation (Vermeulen et al., 2012; Mekonnen and Hoekstra, 2014; Dudley and Alexander, 2017; Springmann et al., 2018a; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2019; Food and Agriculture Organization of the United Nations (FAO), 2020; Crippa et al., 2021). At the same time, much of the world's population has nutrient-poor diets low in fresh fruits, vegetables, grains and legumes, and overconsumption of foods that increase risk of chronic disease, e.g., processed and ultra-processed foods high in sodium, saturated/trans fats, and added sugar (Springmann et al., 2018b; Clark et al., 2019; Global Nutrition Report, 2021). There are 690 million undernourished people and 11 million deaths related to poor diets around the world annually (Global Panel on Agriculture and Food Systems for Nutrition, 2020). With a global population set to peak at almost 10 billion by 2050 (Gu et al., 2021), this "diet-environment-health trilemma" of global food systems (Clark et al., 2018; Hawkins, 2019) requires urgent attention, and has led to calls for a transition to more sustainable food systems (Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO), 2019; Willett et al., 2019; Global Panel on Agriculture and Food Systems for Nutrition, 2020; United Nations Framework Convention on Climate Change (UNFCCC), 2023b). From a demand constraint perspective, the focus has been on changes in consumption patterns and dietary shifts (Heller et al., 2013; Meier and Christen, 2013; Hallström et al., 2015; Notarnicola et al., 2017; Willett et al., 2019). However, at the same time there are concerns about the nutritional inadequacy of some diets (vegan, vegetarian etc.) that have been widely acknowledged as being good for planetary health (Graham et al., 2019; Mazac et al., 2023). Consumers can be supported in their choices for healthy and sustainable foods by having access to easily comprehensible information about a food product's environmental and nutritional credentials in the form of indicators and other metrics (Notarnicola et al., 2015, 2017).

Environmental Life Cycle Assessment (LCA) has been widely used for assessment of the environmental impacts of production and/or packaging, distribution, and consumption of various agri-food products (Schaubroeck et al., 2018; Clark et al., 2022), meals/menus (Calderón et al., 2018; Takacs et al., 2022) and diets (Hallström et al., 2015; Eme et al., 2019; Henriksson et al., 2021). It is recognized as one of the most informative and holistic methods to evaluate environmental impacts associated with agri-food systems (Sala et al., 2017; McAuliffe et al., 2018). The unit of analysis in an LCA is the functional unit (FU), representing the function or service provided by a product system. Food LCAs have traditionally mostly used mass- or volume-based FUs, and do not account for nutritional value (Saarinen et al., 2017; Sala et al., 2017; Sonesson et al., 2017). Yet one of the most critical functions of food is to provide nutrition to support healthy growth, development, and longevity (Willett et al., 2019; World Health Organization (WHO), 2023). This has led to development of a nascent field of study on nutritional LCA (nLCA), defined as an LCA study in which nutrition is considered the main, or one of the main, functions of food (McLaren et al., 2021).

Several nLCA studies assess the quantity (or quality-corrected quantity) of selected individual nutrients in food items and diets, including phenols, protein, fat, calcium, and energy (e.g., Martínez-Blanco et al., 2011; Oonincx and de Boer, 2012; Saarinen et al., 2017; McAuliffe et al., 2018; Berardy et al., 2019; Salazar et al., 2019). However, foods are a complex mix of many macro- and micro-nutrients that are essential for the proper functioning of the human body. Nutritional Profiling (NP) can be used to assess the nutritional value of foods more comprehensively (Drewnowski et al., 2019, 2021). In this approach, the nutritional value is expressed in the form of indices featuring nutrients to encourage, nutrients to limit, and/or a combination of both.

One particular set of indices, the Nutrient Rich Food (NRF) family of indices proposed by Drewnowski (2009) has been comprehensively tested and validated and is increasingly used in nLCA studies (see for example, Van Kernebeek et al., 2014; Doran-Browne et al., 2015; Esteve-Llorens et al., 2019; Hallström et al., 2019; Bianchi et al., 2020; Green et al., 2020, 2021; Ridoutt, 2021; Strid et al., 2021; Aceves-Martins et al., 2022; Mazac et al., 2023). An NRF index is comprised of two indices; one represents nutrients to encourage (NR_n) and the other represents nutrients to avoid or limit (LIM).[1] An NRF index is commonly calculated as the difference between the NR_n and LIM indices. This NRF family of indices can include a variable number of nutrients and can be calculated using nutrient reference values for specific population groups, thus it is easily adapted to suit the requirements of a

1 The NR_n index is calculated as the sum or mean of the ratio of beneficial/qualifying nutrients relative to their associated reference values (e.g., Recommended Dietary Intake, RDI). The LIM index is expressed as the sum or mean of the ratio of disqualifying nutrients to their associated reference values (e.g., Upper Limit (UL) of intake).

particular nLCA study. Several methodological choices have to be made when choosing to use an NRF (or other NP) index. These include the number of nutrients to assess, whether a specific index is chosen for each food group or whether one index is used for all food groups considered in the analysis, the reference amount to be used (e.g., mass-, energy-, or serve size-based), capping/weighting the nutrients, and energy standardization (Scarborough et al., 2010; Masset et al., 2015; Drewnowski, 2017; Saarinen et al., 2017; Hallström et al., 2019; Bianchi et al., 2020; Green et al., 2021, 2023; Strid et al., 2021; Kyttä et al., 2023). Green et al. (2020) note that methodological choices with respect to these variables can significantly alter the assessment of nutritional value of a particular food. However, there is no formal consensus on how to choose the best index-based metric to summarize this nutritional value. Moreover, case studies investigating the influence of these methodological choices in the context of nLCA studies are currently limited (see, for example, Bianchi et al., 2020).

Regarding the selection of nutrients, an index with a limited number of nutrients is sometimes considered most appropriate for nutrient profiling (Fulgoni et al., 2009; Drewnowski, 2017; Green et al., 2020; Weidema and Stylianou, 2020). However, selection of nutrients for nutritional index development should be based on sound justification (Hallström et al., 2019; Bianchi et al., 2020; Ridoutt, 2021; Strid et al., 2021) due to the risk of excluding nutrients that may have an important role to play in human health. The $NRF_{9.3}$ index, comprising nine nutrients to encourage (protein, fiber, calcium, iron, magnesium, potassium, and vitamins A, C, and E) and three nutrients to limit (added sugar, sodium, and saturated fats), is the most widely used and validated NRF index to date (Van Kernebeek et al., 2014; Doran-Browne et al., 2015; Fernández-Ríos et al., 2021). However, the $NRF_{9.3}$ index does not reflect the full nutritional value of a food, and this is particularly relevant for food items with specific characteristics (Kägi et al., 2012; Bianchi et al., 2020). For example, seafoods such as tuna and salmon are a rich source of Polyunsaturated Fats (PUFAs) (Coelho et al., 2016; Salazar et al., 2019), avocados are a good source of Monounsaturated Fats (MUFAs) (Guan et al., 2022), mushrooms are rich in selenium (Falandysz, 2008), and chicken is a good source of selenium and B vitamins like niacin and vitamin B6 (New Zealand Food Composition Database (NZFCD), 2022). However, none of these nutrients are included in the $NRF_{9.3}$ index. In such cases, Bianchi et al. (2020) suggest that an index with a more comprehensive selection of nutrients to encourage, and/or one which is tailored to represent the nutritional profile of the foods being studied, may be more appropriate. For example, Hallström et al. (2019) and Saarinen et al. (2017) developed expanded indices to include all nutrients relevant to the food group being studied. Likewise, Vieux et al. (2013) included all nutrients they considered "key" for diet-related assessments. Another approach is to include all nutrients with formally available Daily Recommended Intake (DRI) and nutrient composition values (Fern et al., 2015; Green et al., 2021, 2023; Ridoutt, 2021).

Combined nutritional and environmental LCA studies have mostly focused on individual food items or diets; there have been relatively fewer combined studies at the meal level. Of these, several studies considered meals based on, or aligned to dietary guidelines, nutritional recommendations (e.g., configuring meals to the Lunch Plate model), or national certification standards for "healthy meals" (Virtanen et al., 2011; Saarinen et al., 2012; García-Herrero et al., 2019; Sameshima et al., 2023). Some studies assumed that the meals being considered are nutritionally adequate (Takacs et al., 2022), while others scaled the meals to have comparable nutritional and/or caloric values, or to similar quantities of foods (Davis et al., 2010; Virtanen et al., 2011; Ernstoff et al., 2019; Sameshima et al., 2023). Thus, these studies did not compare meals based on their individual calculated nutritional value; rather, the latter was kept constant, and the environmental impacts of these nutritionally comparable meals were assessed.

A review of the literature enabled the identification of 11 meal-level studies relevant to this research paper, i.e., meal-level nLCA studies as well as meal-level studies that used environmental and nutritional information to rank meals. Supplementary Table 1 shows that most of the identified studies used integrated methods of analysis.[2] This is related to a common theme in the literature – the discussion around "single scores" representing the combined assessment of both environmental impacts and nutrition to facilitate informed consumer choices (Lukas et al., 2016; Sturtewagen et al., 2016; Schaubroeck et al., 2018; Mazac et al., 2023). Around half of the studies included ranking of meals based on their combined environmental impacts and nutritional value, and a variety of approaches were used to determine the nutritional value of meals. Environmental impacts were assessed in various impact categories, with climate change impacts assessed most frequently. Most of the 11 studies assessed actual meals or meals constructed with real-life data, in university, school, and worksite canteens, care homes, and restaurants (Supplementary Table 1), while only three studies (Lukas et al., 2016; Batlle-Bayer et al., 2020 and Mazac et al., 2023) evaluated theoretical/hypothetical meals. In fact, the importance of using real-life meals to account for social/cultural acceptance was noted for future research (e.g., Batlle-Bayer et al., 2020).

In summary, the literature showed that the integrated approach to combined assessments was the more frequently adopted approach in meal-level studies, and a "real life" meal focus was considered important to the analyses. Moreover, only four nLCA studies were identified that used nutritional indices to compare and rank meals. Three of these studies used the $NRF_{9.3}$ index, and only Mazac et al. (2023) used the NRF approach with more than 9 nutrients to encourage. Therefore, given the outstanding methodological issues related to the use of NRF indices in nLCA studies, this research strives to develop a better understanding of the use of NRF indices in nLCA studies of meals. To do this, different methods were investigated for ranking foods within a simple meal context, using a case study of a New Zealand (NZ)-specific "toppings on toast" (ToTs) meal. The overarching aim of this study is to understand how nLCA can be used to support consumers to make informed food choices based on credible, life cycle-based nutritional and environmental information.

2 In combined environmental and nutritional assessments such as nLCA studies, these two aspects can be assessed in parallel or in an integrated single score approach. With respect to integrated assessments in nLCA studies, the environmental impact of food is calculated relative to a unit of its nutritional value (e.g., Doran-Browne et al., 2015; González-García et al., 2018; Berardy et al., 2019; Chapa et al., 2020; Green et al., 2021; Strid et al., 2021).

2 Methods

A survey was conducted to identify common food choice preferences for ToT meals (Section 2.1). The survey results were used to identify the most commonly consumed toast toppings. For the selected toppings, climate change impact scores (Section 3.1.1), nutritional value scores (Section 3.1.2), and nLCA results (Section 3.1.3) were then calculated.

2.1 Survey of preferred toast toppings

A survey was developed as an online questionnaire using Google Forms, with questions about topping preferences on toast. It was shared with the researchers' personal and professional contacts by email and on social media. Of the 157 respondents, 94% said that they commonly consume toasted or untoasted bread with toppings as a meal or snack option and most respondents preferred to have this for breakfast or lunch. Most of the respondents were fairly evenly distributed between age groups covering 21–60-year-old people, with a smaller proportion aged younger than 20 or over 60 years of age – thus, the survey was fairly representative of the age distribution of adult NZ residents (O'Neill, 2023). Respondents indicated that the most preferred toppings were avocado, tomatoes, cheddar cheese, salmon, tuna, chicken, egg, butter, hummus, mushrooms, banana, honey, jam, nut butters, marmite/vegemite,[3] and bacon. Of these, LCA data was not available for hummus and marmite/vegemite, therefore these specific toppings were excluded from further analysis.

2.2 Climate change scores

The literature on the nutrition-environment nexus and sustainable diets notes a consistent focus on climate change as the priority environmental impact category of interest (Heller et al., 2013; Hallström et al., 2015; Jones et al., 2016; Eme et al., 2019; Guo et al., 2022; Harrison et al., 2022). Given the current climate crisis (United Nations Framework Convention on Climate Change (UNFCCC), 2023a), climate change was considered for the environmental impact analysis. The impact scores, calculated using Global Warming Potential (GWP) over a 100-year timeframe (GWP100), were quantified for each of the selected toppings.

In a recent study, Drew et al. (2020) developed an NZ-specific database of LCA-based climate change impact scores for a comprehensive range of food products aligned with those listed in the New Zealand Food Composition Database. To do this, the authors first screened several available databases based on predefined criteria and then selected the one provided by Hoolohan et al. (2013) as the reference database that matched all the criteria (see Drew et al. (2020) for details on inclusion and exclusion criteria). NZ-specific LCA data was available for the production of some food products; for these products, the farming/processing-related climate change values were used in the new database (for example, tomatoes, wine, cheese, and dairy milk). For other domestically grown food items for which climate change values were unavailable, Greenhouse Gas (GHG) emissions were estimated by averaging NZ-specific farming/processing values of similar food items grown in NZ for which values were available. In cases where this was not possible, the value from the reference database (Hoolohan et al., 2013) was used as a proxy. One exception to this rule was dairy products. For some dairy products which did not have associated NZ-specific emissions data, emission values for the same dairy products in the reference database were adapted to reflect the quantity of NZ dairy milk used in them. The dairy milk emissions estimates in the reference database were based on global data obtained from Food and Agriculture Organization of the United Nations (FAO) (2010). For all the products for which post-production GHG emissions data were unavailable for NZ, values in the reference database were adapted to reflect transport, storage, and distribution within NZ to the point-of-sale. To our knowledge, this is the only comprehensive NZ-specific LCA-based GHG emissions database available currently.

Because the Hoolohan et al. (2013) dataset (used to develop the Drew et al. (2020) dataset) is ten years old and uses LCA values from even earlier years, a decision tree approach was applied to arrive at the most representative and relevant climate change values for the food items selected for this study. Such decision trees have also been used in other areas of quantitative and qualitative research (e.g., Verdinelli and Scagnoli, 2013; Dutton et al., 2015; De Smalen et al., 2021). As shown in Figure 1, the starting point for the decision flowchart was the availability of recent (<5 years old) climate change impact scores for food items that are specific to NZ. The resulting climate change scores for the chosen toast topping, including further details on calculations, are listed in the Supplementary material (Section 1, and Supplementary Table 2).

2.3 Nutritional values

2.3.1 Assignment to food group

The food group categorizations used in this study are listed in the Eating and Activity Guidelines published by the NZ Ministry of Health (2020) (see Supplementary Table 2 for a list of all toppings with the food groups they belong to in this study).[4] These dietary guidelines indicate that processed foods typically high in sugar, saturated/trans fats, and/or salt (e.g., processed meat, cakes, biscuits, butter, honey and jam) should be replaced with nutrient-rich and less processed foods. The NZ dietary guidelines do not categorize these foods separately, but the Australian dietary guidelines suggest a separate category for them called "discretionary foods" (National Health and Medical Research Council, 2013a). Therefore, for this study, four toppings (bacon, butter, jam, and honey) were categorized as "discretionary foods".

3 Yeast spreads commonly consumed in the UK and Commonwealth countries, particularly Australia and New Zealand (Rozin and Siegal, 2003; Vriesekoop et al., 2022).

4 The fourth group in the guidelines is Grains – Grains (bread, rice, pasta, cereals), which in this study is toast and remains constant throughout the study.

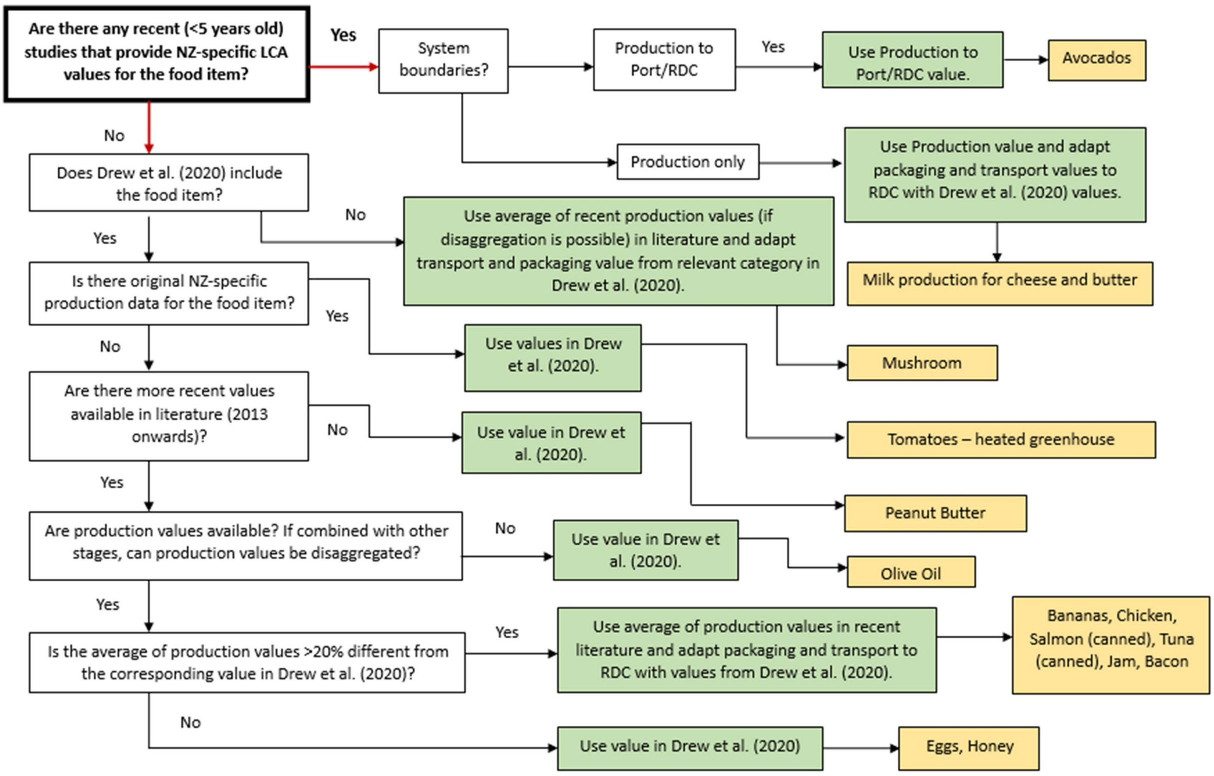

FIGURE 1
Decision tree to identify the climate change impact scores for the toast toppings selected for this study.

2.3.2 Nutritional score

2.3.2.1 Reference unit

This study considers different food items in a simple meal context; therefore, the portion size (which in most cases was the serve size)[5] of individual toppings was selected as the appropriate reference unit (McLaren et al., 2021; Green et al., 2023). Serve sizes for most of the toppings in this study were obtained from the standard values provided in the New Zealand Food Composition Database (NZFCD) (2022) (see Supplementary Table 3 for all serve sizes used in this study). For some of the toppings, adjustments were made so that the assumed amount consumed was more realistic (for example, two rashers of bacon instead of one) guided by the NZ and Australian dietary guidelines (National Health and Medical Research Council, 2013b; Ministry of Health, 2020).

2.3.2.2 Choice of nutrients in indices

The number and type of nutrients included in published nutritional indices varies from 6 to 22 qualifying, and up to three disqualifying nutrients in NRF indices, and up to 27 qualifying and 6 disqualifying nutrients in indices using the Nutrient Balance Concept (NBC) (see Supplementary Table 4 for a list of indices identified in literature). For this study, it was decided to use the NRF family of indices and $NRF_{9.3}$ was chosen as the baseline since it is the most widely used index. However, as discussed in Section 1, $NRF_{9.3}$ includes a limited number of nutrients that do not represent the entire nutritional quality of all foods. Therefore, a more comprehensive nutritional index was compiled that included all the nutrients which appear at least once in the New Zealand Food Composition Database nutritional composition data for each of the 14 toppings, and for which Nutrient Reference Values (NRVs) are also available.[6] This resulted in an index with 28 nutrients to encourage and 3 nutrients to limit. The selected nutrients in both indices are listed in Table 1.

NRVs for each nutrient were obtained from the combined NRV list developed for Australia and NZ by the National Medical Health and Research Council (2017). Some NRVs vary by age and sex and so the mean NRVs for adult men and women (based on the 50:50 ratio of men: women as per Stats NZ, 2023) in the NZ population were used in the analysis. The NRV value for MUFAs was obtained

5 The terms "serve size" and "portion size" are sometimes used interchangeably in literature to represent the quantity of food typically consumed by an individual, however they mean different things (Spanos et al., 2015). Serve size refers to the quantified (measured) value of a food product found on nutrition labels (National Heart Lung and Blood Institute, 2023), whereas portion size refers to the actual quantity that an individual consumes in one sitting for a meal or snack (The Academy of Nutrition and Dietics, 2023).

6 Biotin, molybdenum, and fluoride were excluded as there were no values available for these in the food composition data of the 14 toppings. Published NRVs were unavailable for chloride and sulfur. Some bioactive phytochemicals, like flavonoids and carotenoids, and food additives were excluded from the study because of lack of both available NRVs and standardized composition data.

TABLE 1 Nutrients included in the two nutrient indices used in this study.

Category	Nutrient	$NRF_{9.3}$	$NRF_{28.3}$	NRV	NRV unit
Macronutrients	Dietary fibre	✓	✓	28	g
	Protein	✓	✓	59	g
	Monounsaturated fatty acids (MUFAs)		✓	21	g
	Polyunsaturated fatty acids (PUFAs) – Omega 3		✓	1.1	g
	PUFAs – Omega 6		✓	11	g
Minerals	Calcium	✓	✓	1,129	mg
	Chromium		✓	30	µg
	Copper		✓	1	mg
	Iodine		✓	150	µg
	Iron	✓	✓	10	mg
	Magnesium	✓	✓	368	mg
	Manganese		✓	5,250	µg
	Potassium	✓	✓	1,000	mg
	Phosphorous		✓	3,300	mg
	Selenium		✓	65	µg
	Zinc		✓	11	mg
Vitamins	Folate		✓	400	µg
	Niacin		✓	15	mg
	Pantothenic acid		✓	5	mg
	Riboflavin		✓	1	mg
	Thiamin		✓	1	mg
	Vitamin B12		✓	2	µg
	Vitamin B6		✓	1	mg
	Vitamin C	✓	✓	45	mg
	Vitamin A	✓	✓	800	µg
	Vitamin D		✓	9.3	µg
	Vitamin E	✓	✓	8.5	mg
	Vitamin K		✓	65	µg
Nutrients to limit	Added sugar	✓	✓	52	g
	Saturated fat	✓	✓	24	g
	Sodium	✓	✓	2,300	g

from Drewnowski et al. (2009) (which provided the MUFA value for a 2,000 kcal diet) and adapted to the standard NZ diet of 2,081 kcal as per the Australia New Zealand Food Standards Code [Food Standards Australia New Zealand (FSANZ), 2021]. The Upper Levels (ULs) of intake for saturated fats and sodium were also obtained from Food Standards Australia New Zealand (FSANZ) (2021). The UL for added sugar was adapted to the NZ 2,081 kcal diet from the value provided for an average 2,000 kcal diet in Fulgoni et al. (2009). Weighting and/or capping were not applied to the indices (see Section 4.1.3 for a discussion on this methodological choice).

2.3.2.3 Calculation of nutritional value

All nutritional composition data were obtained from the New Zealand Food Composition Database (NZFCD) (2022). This database considers the sugar content in honey to be both added and free, based on the definition of the two kinds of sugars provided by the United States Food and Drug Administration (Erickson and Slavin, 2015) and the World Health Organization (WHO) (2015). Since honey was studied as a topping/food item (and not as a sweetener) in this study, the sugar content in honey was not considered to be added sugar.

For each topping, the ratio of every nutrient to its NRV was calculated. These ratios can then either be summed, or their mean calculated, to arrive at the NR_n or LIM score. For this study, the NR_n and LIM values were calculated using the mean method (see Eqs. 1 and 2) since the toppings were being evaluated for comparison using two different indices with a different number of nutrients considered in each index. The NRF value was obtained by subtracting the LIM from the NR_n.

$$NR_n = \frac{1}{n} \times \sum_{i=1}^{n} \left(\frac{Nutrient_i}{NRV_i} \right) \quad (1)$$

n = number of beneficial/qualifying nutrients; $Nutrient_i$ = content of beneficial/qualifying nutrient "i" per serve of the topping (g, mg, or µg); NRV_i = the nutrient reference value of beneficial/qualifying nutrient "i" (g, mg, or µg).

And

$$LIM = 1/3 \times \sum_{j=1}^{3} \left(\frac{Nutrient_j}{NR_j} \right) \quad (2)$$

$Nutrient_j$ = content of limiting/disqualifying nutrient per serve of the topping (g or mg); NRV_j = the nutrient reference value of limiting/disqualifying nutrient "j" (g or mg).

2.4 Calculation of nLCA results

For the combined nutritional and environmental analysis (nLCA), the climate change impact scores and nutritional (NR_n, LIM, and NRF) scores per serve size were compiled into one table for the 14 toppings. In addition, these scores were also presented on the basis of the Energy Density (ED) of the food items per serve as recommended in McLaren et al. (2021). The scores for all the toppings within each category (climate change impact, NR_9, NR_{28}, $NRF_{9.3}$, $NRF_{28.3}$, and ED) were divided into quartiles and each quartile assigned a color for a visual representation of the nLCA results. In a next step, the climate change impact, $NRF_{9.3}$ and $NRF_{28.3}$ scores of all the toppings were assigned performance-based values from 1 (worst performance) to 4 (best performance), based on the quartiles. Then two scenarios were established – ranking set A and ranking set B. Set A consisted of the average of the above-mentioned assigned values for climate change and $NRF_{9.3}$ for each of the 14 toppings. Set B used the assigned values for climate change and $NRF_{28.3}$ instead of $NRF_{9.3}$ (See Eqs. 3 and 4). The toppings were then ranked based on the values obtained in these two scenarios.

$$RA_{score} = \left(V_{cc} + V_{9.3} \right) / 2 \quad (3)$$

RA_{score} = ranking score for the topping for ranking set A; V_{cc} = quartile-based value assigned to the topping for its climate change

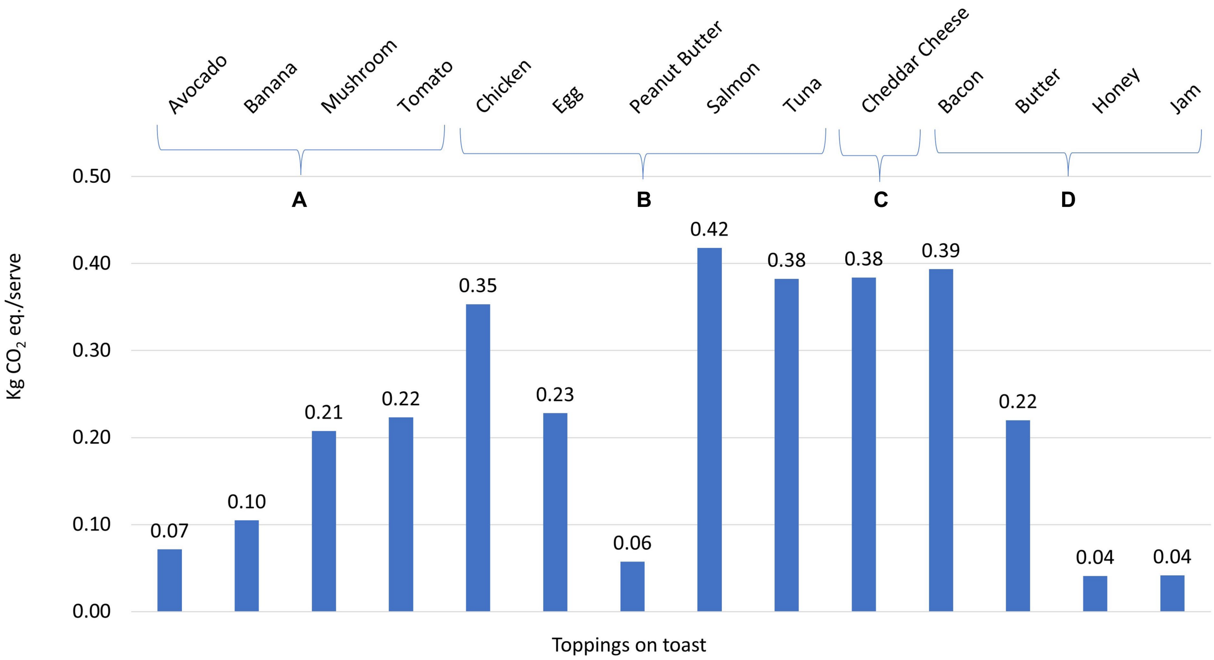

FIGURE 2
Climate change impact scores (kg CO_2 eq./serve) for each of the 14 selected toppings representing the four food groups: **(A)** Vegetables and fruits; **(B)** Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; **(C)** Dairy milk and dairy milk products, mostly low and reduced fat; and **(D)** Discretionary foods.

score; $V_{9.3}$ = quartile-based value assigned to the topping for its $NRF_{9.3}$ score.

And

$$RB_{score} = \left(V_{cc} + V_{28.3}\right) / 2 \quad (4)$$

RB_{score} = ranking score for the topping for ranking set B; V_{cc} = the quartile-based value assigned to the topping for its climate change score; $V_{28.3}$ = quartile-based value assigned to the topping for its $NRF_{28.3}$ score.

In addition, a sensitivity analysis was undertaken using the two other commonly used reference units, mass (per 100 g) and energy (per 100 kcal), using the same method described above.

3 Results

The climate change, nutritional and nLCA results are presented in this section per serve size for the baseline scenario, followed by a comparison of the results when using a mass- or energy-based reference/functional unit.

3.1 Baseline results

3.1.1 Climate change impact scores

Figure 2 shows that the climate change impact scores are higher for the toppings that are products from animals rather than plants; canned salmon has the highest impact score with 0.42 kg CO_2 eq./serve, followed closely by bacon, cheddar cheese, tuna, and chicken. Avocados and bananas had the lowest impact scores among the fresh plant-based foods with 0.07 and 0.10 kg CO_2 eq./serve, respectively. Jam and honey (0.04 kg CO_2 eq./serve each) had the lowest climate change impacts of all the 14 toppings.

3.1.2 Nutritional analysis

The NR_n and LIM scores are shown in Figure 3. Butter had the highest LIM score (0.33), followed by bacon (0.25) and cheddar cheese (0.17). When considering the NR_9 index, chicken and honey had the highest (0.1) and lowest (0.001) scores respectively; for the NR_{28} index, tuna and salmon had the highest scores (0.18 and 0.17 respectively) and jam the lowest score (0.002).

The NR_{28} scores were higher than the NR_9 ones for most of the toppings. The largest change (%) from the NR_9 to NR_{28} score was noted in tuna (nearly 200% higher) (Figure 4). This was followed by salmon, bacon, honey, and mushrooms – all of which showed >100% increase from the NR_9 score. The exceptions to this trend were tomatoes, bananas, cheddar cheese, and jam. The lower NR_{28} scores (relative to NR_9) for these four toppings can be attributed to the presence of relatively smaller quantities of other nutrients (not included in NR_9), which reduced the mean value of the nutrient to NRV ratios used to calculate the NR_n indices. To illustrate, the largest increase from NR_9 to NR_{28} scores was noted for tuna (as mentioned above) and the largest decrease for tomato. For tuna, the nutrients common to both indices contributed only 11% to the total NR_{28} score; for tomato, 66% of the contribution to the total NR_{28} score was from the common nutrients (see Supplementary Table 5).

The overall trend of the majority of the toppings displaying higher NR_{28} scores compared to NR_9 can be attributed to the

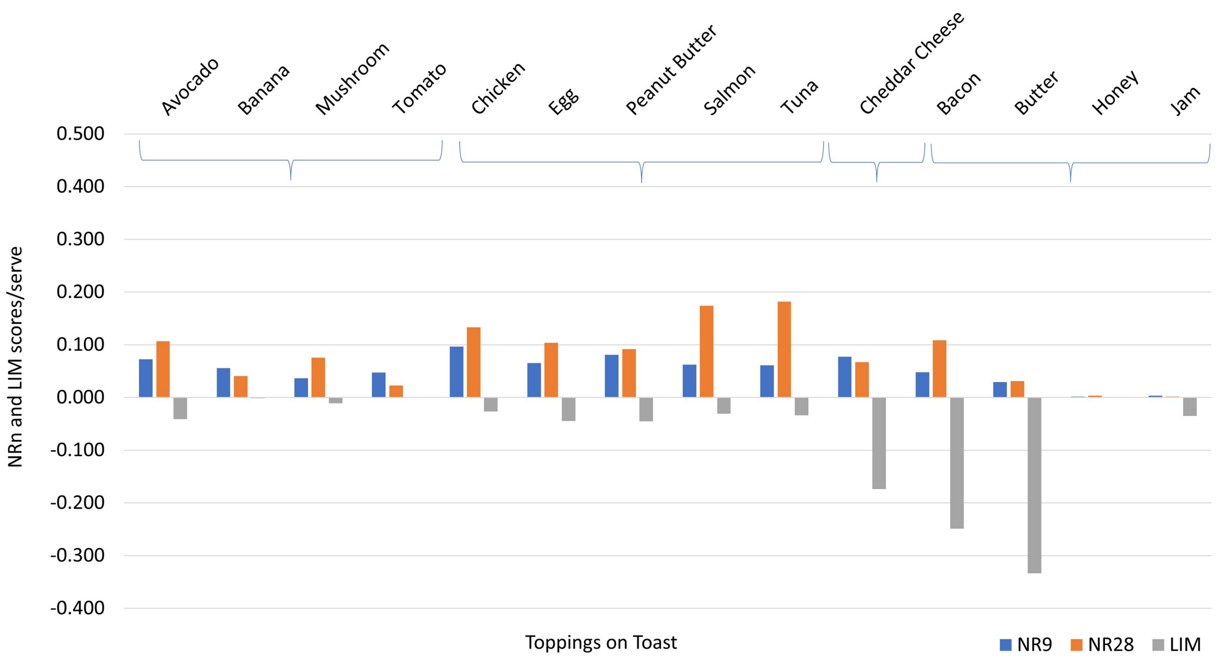

FIGURE 3
NR_n and LIM values for 9 and 28 qualifying and 3 disqualifying nutrients for each of the 14 toppings representing the four food groups: **(A)** Vegetables and fruits; **(B)** Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; **(C)** Dairy milk and dairy milk products, mostly low and reduced fat; and **(D)** Discretionary foods.

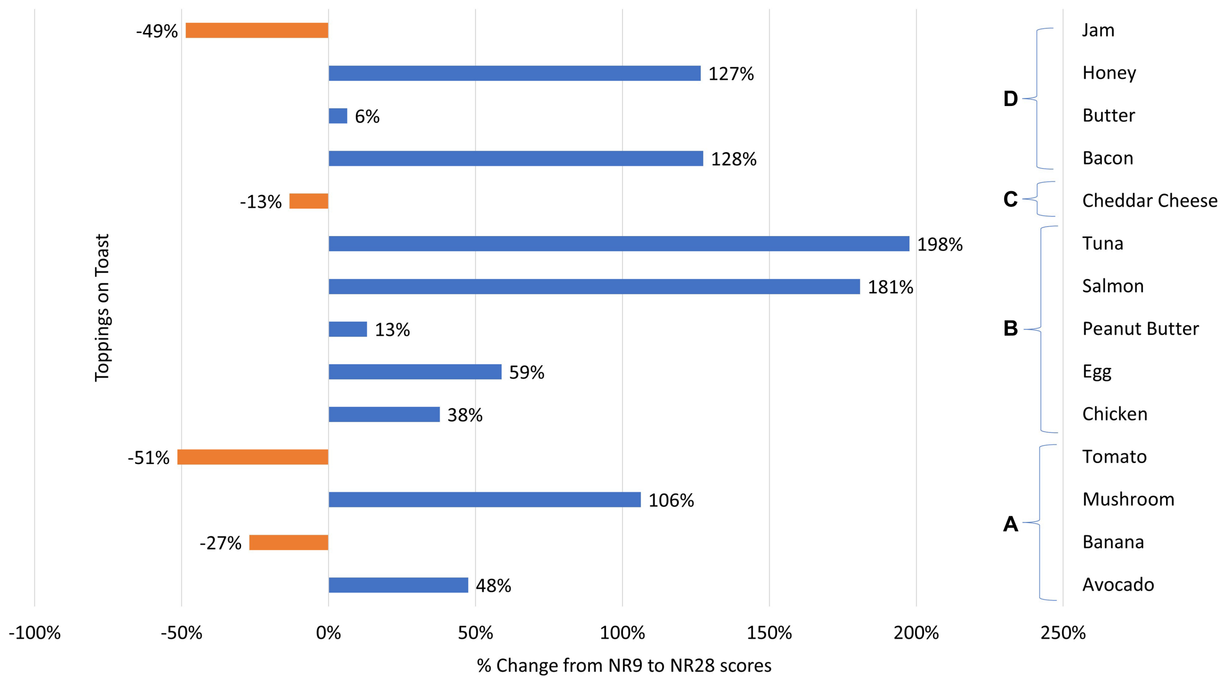

FIGURE 4
Change (%) from NR_9 to NR_{28} scores of the 14 toppings representing the four food groups: **(A)** Vegetables and fruits; **(B)** Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; **(C)** Dairy milk and dairy milk products, mostly low and reduced fat; and **(D)** Discretionary foods.

inclusion of a larger number of water-soluble vitamins (as well as minerals and unsaturated fats to a lesser extent) in the NR_{28} index (see contribution analysis in Figures 5, 6). Minerals, fat-soluble vitamins, and proteins were the main contributors to the NR_9 score of most of the toppings (accounting for 38, 23, and 22% to the total score on average), with water-soluble vitamins accounting for only

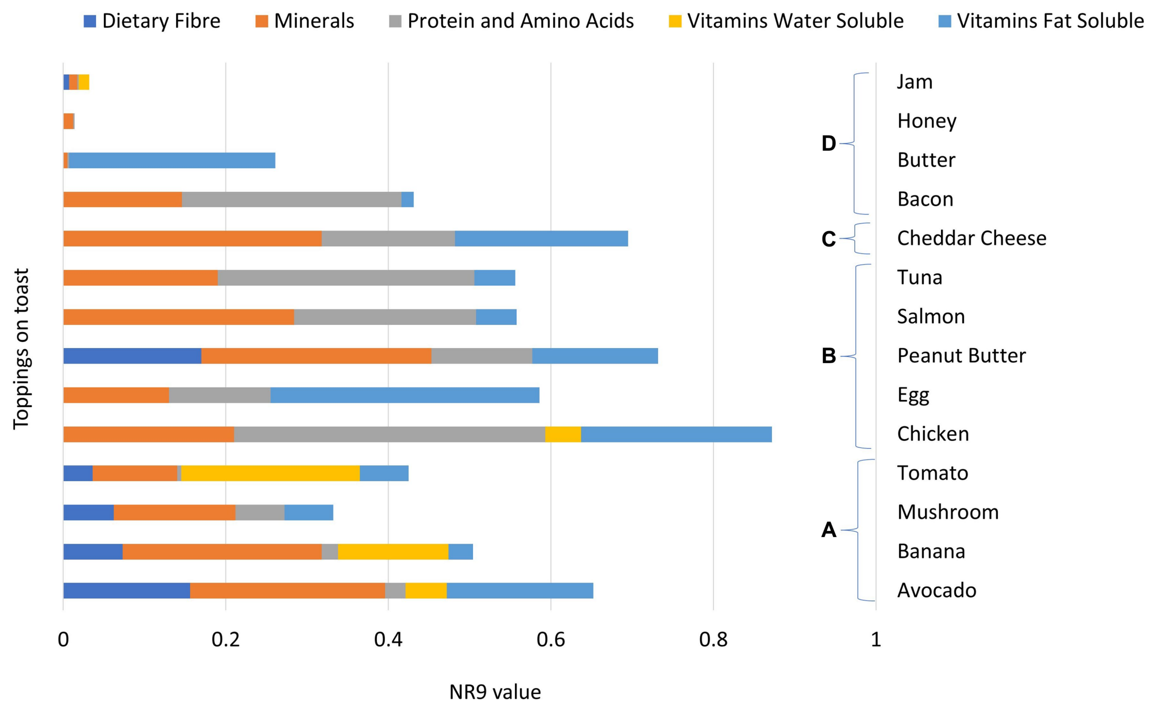

FIGURE 5
Contribution of nutrient categories to NR_9 values for each of the 14 selected toast toppings representing the four food groups: **(A)** Vegetables and fruits; **(B)** Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; **(C)** Dairy milk and dairy milk products, mostly low and reduced fat; and **(D)** Discretionary foods.

9% of the total score on average. There was no contribution of dietary fiber to the total NR_9 scores of the animal-based toppings, but it accounted for 9–24% of the total NR_9 score for all the plant-based toppings, with the highest contribution in avocados (24%). However, when using the NR_{28} index, the average contribution of water-soluble vitamins to the total NR_{28} score increased to 39%, while the average contribution of fat-soluble vitamins and proteins dropped to 10 and 4% of the total score, respectively. Mineral contribution also decreased, but to a lesser extent (28% of total), while unsaturated fat, now represented in the NR_{28} index, accounted for 17% of the total score on average. Average dietary fiber contribution was the lowest at 3% of the total NR_{28} score.

With respect to the three toppings with the largest LIM scores (bacon, butter, and cheese), sodium was the main contributor to the LIM score for bacon (70%), while saturated fatty acids contributed the most to the LIM scores for butter and cheese (95 and 75% respectively) (Figure 7). Added sugar was present in only one topping (jam) and accounted for almost its entire LIM value.

Butter, bacon, cheddar cheese and jam had negative scores for both the $NRF_{9.3}$ and $NRF_{28.3}$ indices (Figure 8). This is explained by the relatively high LIM scores for butter, bacon, and cheese, compared to the other toppings. In the case of jam, the low NR_n value combined with the higher LIM value resulted in its negative NRF score. The $NRF_{28.3}$ values for most of the toppings were higher than their $NRF_{9.3}$ scores. Of these, the largest difference between the $NRF_{9.3}$ and $NRF_{28.3}$ indices was for salmon and tuna with the $NRF_{28.3}$ scores being ~5 times more than the $NRF_{9.3}$ value for both. This general trend of higher scores for the $NRF_{28.3}$ index was also seen in the NR_n comparisons in Figure 3 as mentioned earlier (where the NR_{28} scores were higher than the NR_9 scores for most of the toppings). As with the NR_n scores, the exceptions to this trend were banana, tomato, cheddar cheese, and jam.

3.1.3 nLCA scores

The nLCA results for the toppings are presented in Table 2. This table effectively represents the climate change impact scores alongside a separate midpoint nutrition impact category comprising the NRF scores. For the ranking process, a weighting value from 1 (worst) to 4 (best) was assigned to each of the quartiles for climate change, and the $NRF_{9.3}$ and $NRF_{28.3}$ scores. Only the NRF values were used in this part of the analysis because they include both nutrients to limit and encourage. Two ranking sets were then calculated: set A is the average of the toppings' climate change and $NRF_{9.3}$ quartile ranking weights, and set B is the average of the toppings' climate change and $NRF_{28.3}$ quartile ranking weights (Table 3). Peanut butter and avocado ranked in the top two positions (best scores) in both ranking sets A and B. Cheddar cheese and bacon rank lowest and butter second to last (worst scores) in both ranking sets. Overall, the ranking of the toppings does not change significantly between the two ranking sets – in fact, all the toppings just move up or down one position between the ranking sets except tomato, which changes by two positions.

3.2 Comparison of results using other reference units

The nLCA results for the 14 toppings are presented for each of the three FUs in Table 4. When using different FUs, the climate

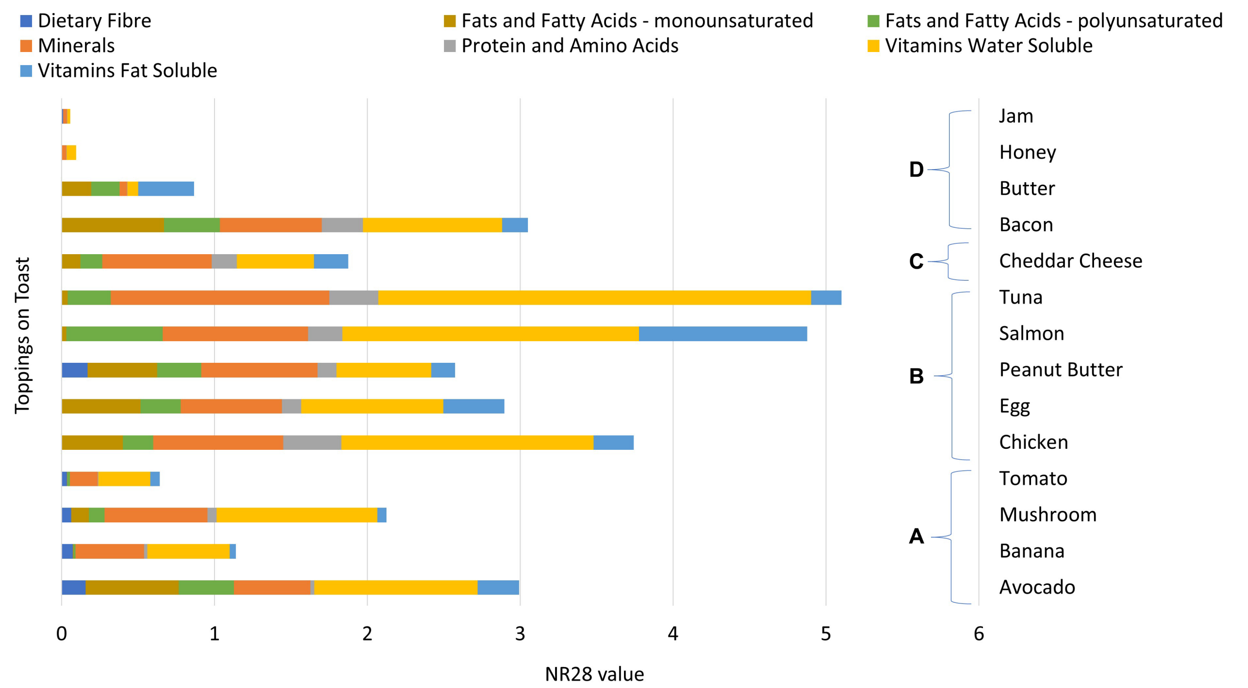

FIGURE 6
Contribution of nutrient categories to the NR_{28} values for each of the 14 selected toast toppings representing the four food groups: **(A)** Vegetables and fruits; **(B)** Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; **(C)** Dairy milk and dairy milk products, mostly low and reduced fat; and **(D)** Discretionary foods.

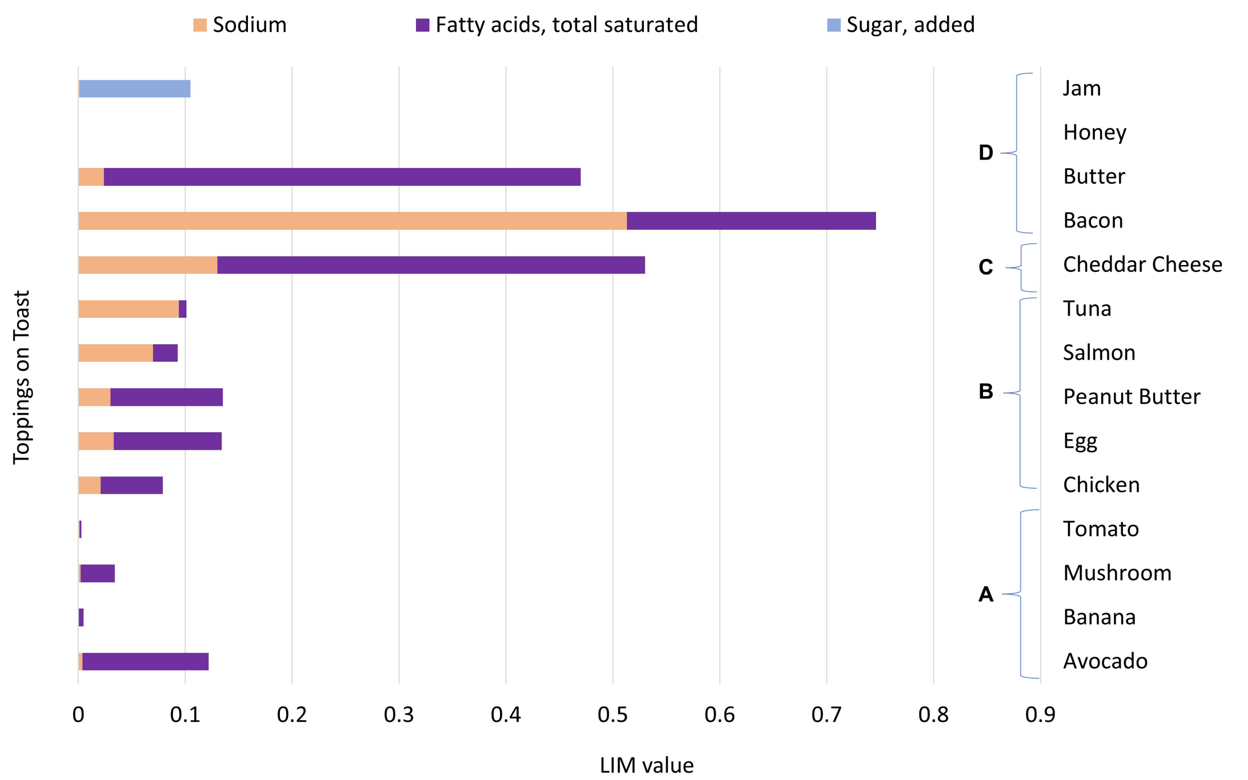

FIGURE 7
Contribution of the three disqualifying nutrients to the LIM scores for each of the 14 selected toast toppings representing the four food groups: **(A)** Vegetables and fruits; **(B)** Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; **(C)** Dairy milk and dairy milk products, mostly low and reduced fat; and **(D)** Discretionary foods.

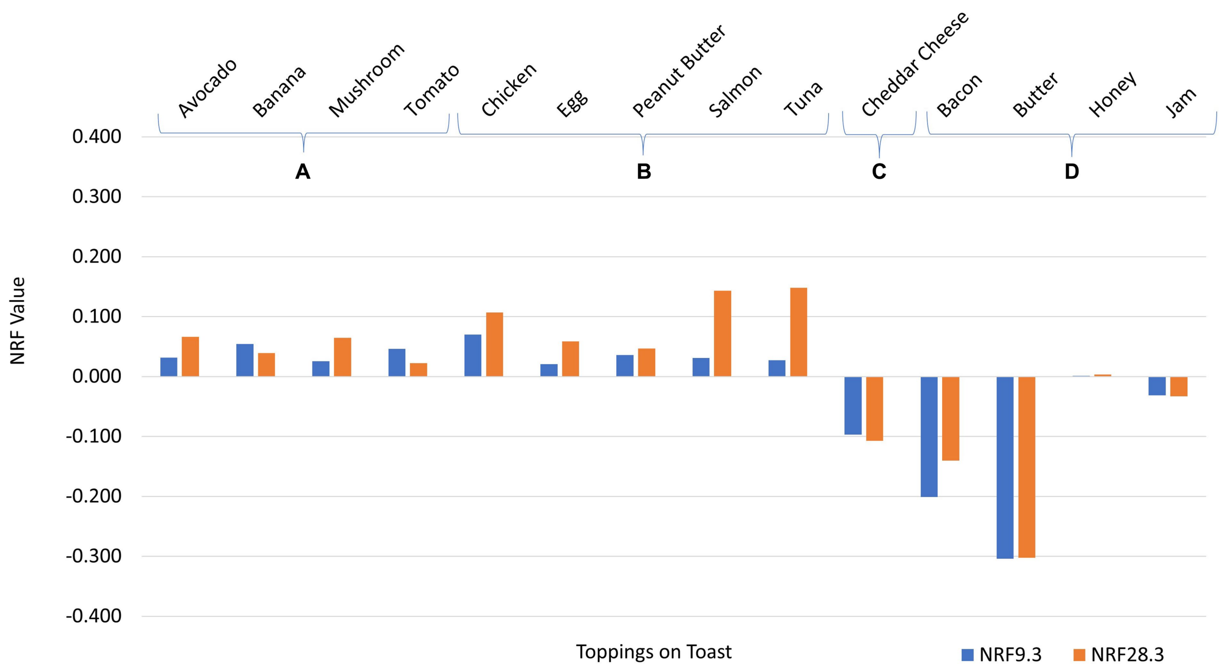

FIGURE 8
$NRF_{9.3}$ and $NRF_{28.3}$ values for all the 14 selected toast toppings representing the four food groups: **(A)** Vegetables and fruits; **(B)** Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat with fat removed; **(C)** Dairy milk and dairy milk products, mostly low and reduced fat; and **(D)** Discretionary foods.

change results for some toppings differ markedly. In particular, for tomato the climate change result is 8.5 times higher when using the 100 kcal rather than serve size as the reference unit. The topping with the highest climate change result is different for each reference unit: salmon based on serve size, butter per 100 g, and tomato per 100 kcal. Overall, vegetables, fruits and protein-rich foods perform better nutritionally and environmentally across all three reference units, whereas cheese and toppings that are considered discretionary foods have the lowest scores.

In a subsequent step, the toppings were ranked using the combined climate change impact and nutritional scores as per Section 3.1.3. Two ranking sets (A and B) were assessed for the two additional FUs – mass (100 g) and energy (100 kcal). These ranking sets are presented in Table 5 along with the baseline ranking set (i.e., per serve size). Avocado, peanut butter and banana appear in the top two ranks for the three FUs in ranking set A. While tomato is ranked second per serve and per 100 g in ranking set A, it moves down two ranks with the 100 kcal FU. For ranking set B, avocado and peanut butter appear in the top two ranks for all three scenarios. Comparing across the two ranking sets, peanut butter and avocado are in the first two ranks, and butter, bacon, and cheddar cheese are in the last two ranks, across all three scenarios in both ranking sets. The change in the ranking position of food items between ranking set A and B is outlined in Supplementary Table 6 for each topping across the three FUs. The toppings which change ranks between the two ranking sets for each FU, move up or down by only one place with two exceptions. The first exception is mushroom which moves down two places in Scenario B per 100 g, and the second is tomato which moves down two places in scenario B per serve size and per 100 g.

4 Discussion

4.1 Methodological choices

4.1.1 Nutrients to consider in indices

The baseline results show that the inclusion of different numbers of nutrients in a scoring system changes the nLCA results for food items in a meal context (Table 2). However, this is not sufficient to change the ranking of the toppings more than one place in the two ranking systems used in this study (Table 3). Tomato is an exception – it changes from second to fourth place in the ranking using $NRF_{9.3}$ and $NRF_{28.3}$ index, respectively. This occurs because the NR_n score for tomato is significantly lower (>50%) for 28 compared to 9 nutrients to encourage. This is due to the presence of Vitamin C in tomato in significant proportions in both indices and relatively smaller contributions by the additional nutrients in the NR_{28} index. Interestingly, the difference between the NR_9 and NR_{28} indices for jam was very similar to that for tomato – its NR_{28} score was 49% lower than its NR_9 score, however, its ranking did not change between the ranking sets. This could be a result of its significantly lower climate change impact score (82%), and higher LIM score (34%) relative to tomato. Thus, this study shows that, as some foods contain certain nutrients (included in the NR_9 index) in more significant proportions than others (for example, calcium in cheese, dietary fibre in the plant-based toppings, and protein in most of the animal-based ones), these nutrients contribute significantly to the NR_9 score of these toppings. However, using an expanded index can "dilute" the total score because of the additional nutrients (not included in NR_9) in the expanded index which only make very small contributions to the total score.

TABLE 2 **nLCA results presented per serve for the environmental (climate change impact) and nutritional values (NR_n, LIM, NRF, and Energy Density) for each of the 14 selected toast toppings, color-coded by the quartile in which each score is categorized.**

	Vegetables and fruits				Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat					Dairy milk and dairy milk products, mostly low and reduced fat	Discretionary foods			
	Avocado	Banana	Mushroom	Tomato	Chicken	Egg	Peanut Butter	Salmon	Tuna	Cheddar Cheese	Bacon	Butter	Honey	Jam
GWP (kg CO_2 eq./serve)	0.07	0.10	0.21	0.22	0.36	0.23	0.06	0.42	0.38	0.38	0.40	0.22	0.04	0.04
NR_9	0.07	0.06	0.04	0.05	0.10	0.07	0.08	0.06	0.06	0.08	0.05	0.03	0.001	0.00
NR_{28}	0.11	0.04	0.08	0.02	0.13	0.10	0.09	0.17	0.18	0.07	0.11	0.03	0.003	0.00
LIM	0.04	0.00	0.01	0.00	0.03	0.04	0.05	0.03	0.03	0.17	0.25	0.33	0.000	0.03
$NRF_{9.3}$	0.03	0.05	0.03	0.05	0.07	0.02	0.04	0.03	0.03	−0.10	−0.20	−0.30	0.001	−0.03
$NRF_{28.3}$	0.07	0.04	0.06	0.02	0.11	0.06	0.05	0.14	0.15	−0.11	−0.14	−0.30	0.003	−0.03
Energy Density (ED) (kcal)	185	105	58	12	155	134	189	84	96	168	232	147	61	47

Assigned ranking weights	Assigned color codes for quartiles	GWP	NR_9	NR_{28}	LIM	$NRF_{9.3}$	$NRF_{28.3}$	ED
4		≤ 0.07	≥ 0.07	≥ 0.11	≤ 0.01	≥ 0.04	≥ 0.07	≤ 61
3		> 0.07 ≤ 0.22	≥ 0.06 < 0.07	≥ 0.08 < 0.11	> 0.01 ≤ 0.03	≥ 0.03 < 0.04	≥ 0.04 < 0.07	> 61 ≤ 120
2		> 0.22 ≤ 0.38	≥ 0.04 < 0.06	≥ 0.03 < 0.08	> 0.03 ≤ 0.05	≥ −0.03 < 0.03	≥ −0.03 < 0.04	> 120 ≤ 168
1		> 0.38	< 0.04	< 0.03	> 0.05	< −0.03	< −0.03	> 168

TABLE 3 Ranking sets A and B for toppings, based on assigned values for quartile-categorized scores for climate change, $NRF_{9.3}$ and $NRF_{28.3}$ (RA_{scores} and RB_{scores}).

Ranking Score	Ranking Set A (based on RA_{scores})	Ranking Set B (based on RB_{scores})
4 (best)	Peanut Butter	Avocado
3.5	Avocado, Banana, Tomato	Peanut Butter
3	Chicken, Honey, Jam, Mushroom	Banana, Chicken, Honey, Jam, Mushroom, Tuna
2.5	Tuna	Egg, Salmon, Tomato
2	Butter, Egg, Salmon	Butter
1.5	–	–
1 (worst)	Bacon, Cheddar Cheese	Bacon, Cheddar Cheese

The nutrient contribution analyses (Figures 5–7) offer some interesting insights. Unlike the NR_9 index, where the proteins and fat-soluble vitamins contribute more to the total score than water-soluble vitamins, the latter usually dominate the NR_{28} index relative to the proteins and fat-soluble vitamins. Thus, water-soluble vitamins gain significance (from the perspective of proportional contribution to the total nutritional value) when an expanded index is used. This has implications for diets deficient in micronutrients, especially in Low- and Middle-Income Countries (LMICs). In particular, "priority micronutrients"[7] include two water-soluble vitamins (folate and vitamin B12) (Beal and Ortenzi, 2022), neither of which are included in the NR_9 index. Thus, it is recommended to include these in nLCA studies when a more nuanced approach is needed to study a population whose diet is lacking in these essential micronutrients (Katz-Rosene et al., 2023).

Secondly, most toppings in this case study contain unsaturated fats and these contributed markedly to the NR_{28} values of several toppings. A number of national and international nutritional guidelines encourage dietary substitution of trans and saturated fats with foods containing MUFAs and PUFAs (especially omega 3 and 6) (National Health and Medical Research Council, 2013a; Ministry of Health, 2020; World Health Organization (WHO), 2023) due to their reported positive impacts on human health (Mozaffarian et al., 2010; Ravaut et al., 2021). Green et al. (2020) also notes that not accounting for healthy fats penalizes foods that are rich in them. Although the rankings did not change significantly in this study when including additional nutrients in the $NRF_{28.3}$ index, the presence of MUFAs and PUFAs was instrumental in moving some of the toppings up a rank, e.g., avocados, tuna and eggs. Therefore, if food composition data on MUFAs and PUFAs is available, it might be useful to include them in studies focused on comparing/ranking foods within meals or meals themselves.

Overall, the results of this study align with the views of other authors who note that limiting the number of nutrients in nutritional profiling algorithms can be sufficient to obtain a representative understanding of the nutritional value of food items or diets (as mentioned in Section 1). The rankings obtained in this study did not change much between indices; for example, the top two best and worst performing foods were the same in both. However, with specific food items that are significantly richer in certain nutrients not included in indices with fewer nutrients to encourage, it could be useful to expand the index to include them, as this does affect the final rankings to some extent. For example, avocados (rich in MUFAs) ranked second when using the $NRF_{9.3}$ index but moved up a rank to become the best performing topping with $NRF_{28.3}$. It is also important to note that these findings are specific to this study and could change if other toppings were considered (because the rankings are relative within the studied toppings). Thus, overall, the choice of nutrients considered for the index will also depend on the diversity of the food items/meals being studied – a more diverse range of foods could benefit from an expanded index, to allow for a better representation of the nutritional (and consequently nLCA) value of those foods.

4.1.2 Choice of functional unit

While choice of FU influences the nLCA values, it does not appear to alter the topping rankings significantly (Tables 4, 5).

Food-related LCA studies usually use mass-based FUs; however, when assessing food choices within a meal context, it is preferable to use serve size rather than equal mass-based units as it reflects more realistic consumption and hence nutrient intakes at the meal or diet level (Masset et al., 2014; Grigoriadis et al., 2021; Jolliet, 2022). The only challenge is that, unlike foods within the same food group that are likely to have similar serve sizes as they are commonly standardized by the amount of dietary energy provided in a serve (see, for example, Hallström et al. (2019) who studied seafood), serve sizes are generally not standardized across different food items from different food groups within meals.[8] Moreover, while standardized serve sizes can be useful for comparative studies like the current study, the actual amounts/portions consumed may vary substantially between people and for different consumption situations (for instance, a small snack versus a meal or component of a dish). One solution to variable serve- and portion sizes is using an energy-based metric energy either on a 100 kcal basis or standardized to the recommended daily energy intake (usually ~2,000 kcal). Energy-based FUs account for variable water quantities or calorific densities of different food items, and therefore can make it possible to calculate nutritional value of food independent of portion or serve size (Drewnowski, 2005; Fern et al., 2015; Schaubroeck et al., 2018). Although some argue in favor of using such energy-based metrics (see for example, Green et al., 2023), serve size is still the most representative of actual amounts consumed in one sitting, and therefore more pertinent to the meal context. In fact, Bianchi et al. (2020) suggest that if standardized serve sizes are developed in future, that are also aligned with international standards, then it should be considered a "preferred choice" for FU selection in nLCA studies.

7 These include six micronutrients which diets in LMICs are most frequently deficient in – iron, zinc, folate, vitamin B12, vitamin A, and calcium.

8 An exception to this is the U.S. Reference Amount Customarily Consumed (RACC) – a metric developed and mandated by the U.S. Food and Drug Administration (FDA) to roughly standardize actual serve sizes for a food product (Drewnowski, 2017; Berardy et al., 2019; Grigoriadis et al., 2021).

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TABLE 4 nLCA results for all 14 selected toast toppings, with respect to three reference units – mass, energy, and serve size (bl stands for baseline) color-coded by the quartile in which each score is categorized.

	Vegetables and Fruits				Legumes, nuts, seeds, fish and other seafood, eggs, poultry, or red meat					Dairy milk and dairy milk products, mostly low and reduced fat	Discretionary Foods			
	Avocado	Banana	Mushroom	Tomato	Chicken	Egg	Peanut Butter	Salmon	Tuna	Cheddar Cheese	Bacon	Butter	Honey	Jam
GWP (kg CO_2 eq./ serve)_bl	0.07	0.10	0.21	0.22	0.35	0.23	0.06	0.42	0.38	0.38	0.39	0.22	0.04	0.04
$NRF_{9.3}$ _serve_bl	0.03	0.05	0.03	0.05	0.07	0.02	0.04	0.03	0.03	−0.10	−0.20	−0.30	0.00	−0.03
$NRF_{28.3}$ _serve_bl	0.07	0.04	0.06	0.02	0.11	0.06	0.05	0.14	0.15	−0.11	−0.14	−0.30	0.00	−0.03
GWP (kg CO_2 eq./100 g)	0.08	0.09	0.26	0.28	0.45	0.46	0.19	0.73	0.55	0.96	0.79	1.10	0.20	0.26
$NRF_{9.3}$ _mass_100 g	0.04	0.05	0.03	0.06	0.09	0.04	0.12	0.05	0.04	−0.24	−0.37	−0.64	0.01	−0.20
$NRF_{28.3}$ _mass_100 g	0.08	0.03	0.08	0.03	0.13	0.12	0.16	0.25	0.21	−0.27	−0.28	−0.63	0.02	−0.21
GWP (kg CO_2 eq./100 kcal)	0.04	0.10	0.69	1.86	0.62	0.25	0.03	0.50	0.40	0.23	0.41	0.15	0.07	0.09
$NRF_{9.3}$ _energy_100 kcal	0.02	0.05	0.04	0.39	0.06	0.02	0.02	0.04	0.03	−0.06	−0.10	−0.09	0.00	−0.07
$NRF_{28.3}$ _energy_100 kcal	0.04	0.04	0.11	0.18	0.10	0.07	0.02	0.17	0.15	−0.06	−0.07	−0.09	0.01	−0.07

Assigned ranking weights	Assigned color codes for quartiles	GWP/ serve_bl	$NRF_{9.3}$ _ serve_bl	$NRF_{28.3}$ _ serve_bl	GWP/100 g	$NRF_{9.3}$ _ mass_100 g	$NRF_{28.3}$ mass_100 g	GWP/100 kCal	$NRF_{9.3}$ _ energy_100 kcal	$NRF_{28.3}$ _energy_100 kcal
4		≤ 0.07	≥ 0.04	≥ 0.07	≤ 0.2	≥ 0.05	≥ 0.13	≤ 0.09	≥ 0.04	≥ 0.11
3		> 0.07 ≤ 0.22	≥ 0.03 < 0.04	≥ 0.04 < 0.07	> 0.2 ≤ 0.36	≥ 0.04 < 0.05	≥ 0.06 < 0.13	> 0.09 ≤ 0.25	≥ 0.02 < 0.04	≥ 0.04 < 0.11
2		> 0.22 ≤ 0.38	≥ − 0.03 < 0.03	≥ − 0.03 < 0.04	> 0.36 ≤ 0.73	≥ − 0.2 < 0.04	≥ − 0.21 < 0.06	> 0.25 ≤ 0.5	≥ − 0.06 < 0.02	≥ − 0.06 < 0.04
1		> 0.38	< −0.03	< −0.03	> 0.73	< −0.2	< −0.21	> 0.5	< −0.06	< −0.06

TABLE 5 Toppings ranked as per the two ranking scenarios*, across three FUs (serve, mass and energy).

Ranking Score	Ranking Scenario A (per serve)	Ranking Scenario A (per 100 g)	Ranking Scenario A (per 100 kcal)	Ranking Scenario B (per serve)	Ranking Scenario B (per 100 g)	Ranking Scenario B (per 100 kcal)
4 (best)	Peanut Butter	Banana, Peanut Butter	–	Avocado	Peanut Butter	–
3.5	Avocado, Banana, Tomato	Avocado, Tomato	Avocado, Banana, Peanut Butter	Peanut Butter	Avocado	Avocado
3	Chicken, Honey, Jam, Mushroom	Chicken, Honey, Salmon	Egg, Honey, Salmon	Banana, Chicken, Honey, Jam, Mushroom, Tuna	Banana, Chicken, Honey, Mushroom, Salmon, Tuna	Egg, Banana, Honey, Peanut Butter, Salmon, Tuna
2.5	Tuna	Jam, Tuna, Egg, Mushroom	Cheddar Cheese, Chicken, Mushroom, Jam, Tomato, Tuna	Egg, Salmon, Tomato	Egg, Jam, Tomato	Cheddar Cheese, Jam, Mushroom, Tomato
2	Butter, Egg, Salmon	–	Butter	Butter	–	Bacon, Butter, Chicken
1.5	–	Cheddar Cheese	Bacon	–	–	–
1 (worst)	Bacon, Cheddar Cheese	Bacon, Butter	–	Bacon, Cheddar Cheese	Bacon, Butter, Cheddar Cheese	–

*Ranking Scenario A - average of climate change impact and $NRF_{9.3}$ assigned values; Ranking Scenario B – average of climate change impact and $NRF_{28.3}$ assigned values.

4.1.3 Weighting and capping

Most nLCA studies exclude a specific weighting process, i.e., they weight all the nutrients equally due to a lack of scientific consensus on the appropriate criteria to use for this purpose (Drewnowski, 2017; Green et al., 2020). Some authors recommend weighting of nutrients in an index using the distance-to-target approach, i.e., dividing the DRI by the average intake of that nutrient (Hallström et al., 2019; Bianchi et al., 2020; Ridoutt, 2021; Strid et al., 2021). Some data is available in the NZ Nutrition Survey of 2011 (University of Otago and Ministry of Health, 2011) for the Estimated Prevalence of Inadequate Intake (EPII) of certain nutrients in NZ adults and could potentially be used to develop a scarcity-weighted index. However, using >10-year-old data would probably not be adequately representative of the current situation. Moreover, the survey contains EPII data for only 12 nutrients and excludes, for example, Vitamin D, folate, and iodine. However, if more up-to-date data were available, this would be an interesting extension to the analysis.

Capping refers to restricting the "good" nutrients to 100% of their RDI to avoid over-counting their benefits if there are large amounts in the studied food items. Capping has been applied in several nLCA studies (e.g., Arsenault et al., 2012; Van Kernebeek et al., 2014; Doran-Browne et al., 2015; Drewnowski et al., 2015; Hallström et al., 2019; Batlle-Bayer et al., 2020; Green et al., 2021), but there is currently no consensus on its use (McLaren et al., 2021; Kyttä et al., 2023). Some researchers suggest that, within the diet (i.e., at the food item or meal-level), nutrients should be left uncapped (Hallström et al., 2018; Mazac et al., 2023), because generally diets comprise a diverse range of foods and if a food has lower levels of a particular nutrient, this is compensated by other foods with higher quantities of that nutrient. Green et al. (2023) recommends that nutrients should be capped in a total diet-level study because it represents a complete set of nutrients and therefore, these should not exceed RDIs. Green et al. (2023) also suggest that consuming a particular nutrient in excess of its recommended value not only provides no additional benefits but can even be harmful to health. However, while this may be true for some nutrients, other nutrients may actually have beneficial health impacts when present in concentrations higher than the RDI. For example, certain vitamins, minerals like selenium, PUFAs like omega 3, and dietary fibre have been noted to lower the risk of chronic health issues like heart disease, cancer, and degenerative cognitive issues like Alzheimer's when consumed at levels above the RDI (National Medical Health and Research Council, 2017). As the current study was focused on a single meal and none of the nutrients in the studied food items exceeded their RDIs per serve, this was not a relevant consideration.

4.1.4 Other choices

Other methodological choices made in this study that affected the ranking of the different meals include:

Quantile-based ranking: Toppings were categorized into quartiles based on their nutritional and climate change impact scores. Other studies have used quintiles (e.g., Bianchi et al., 2020; Strid et al., 2021; Green et al., 2023). The choice of such quantiles will depend upon the number of alternatives considered and the range of the results. One challenge with quantile-based ranking is that the results may have to be re-calculated if toppings are excluded or added. However, this is only required if their values are very different from the range of values in the rest of the sample.

Weighting of climate change impacts and nutritional value: These two aspects were weighted equally. However, weighting in LCA implies value judgments and equal weighting may not be representative of how much importance consumers place on nutritional versus climate change impacts. One way to address this is to offer the consumer the option to use their own value judgements. For example, on a website or app employing this method, a tab could be included where the consumer could input their own preference-based weights, and the final scores would be calculated accordingly. This weighting process could potentially also be extended to additional environmental impacts if more environmental impact categories were included in the analysis.

Bioavailability of nutrients: Nutrient bioavailability refers to the "fraction of an ingested nutrient that becomes available for use and storage in the body" (Melse-Boonstra, 2020). Bioavailability is an important aspect of nutritional studies because it explains how the consumption of a nutrient translates into actual health effects. Protein bioavailability has been studied with respect to its quality, i.e., the digestibility of the different amino acids (using for example, the DIAAS score) within plant- and animal-based proteins (Bailey and Stein, 2019; Adhikari et al., 2022), linking protein quality and food sustainability (Moughan, 2021) and incorporating protein quality in nLCA studies (Sonesson et al., 2017; Berardy et al., 2019; McAuliffe et al., 2022). Animal-sourced foods are generally found to contain protein and some essential micronutrients in more bioavailable forms than plant-based foods (Beal et al., 2023). For example, iron is present in food as heme and non-heme iron; however, heme iron is only found in animal-based foods and is more bioavailable than non-heme iron. Similarly, zinc and calcium are generally less bioavailable from plant-based compared to animal-derived foods due to the presence of antinutrients like phytates and oxalates in plants (although the concentrations of these will vary with each food) (Maares and Haase, 2020; Melse-Boonstra, 2020; Shkembi and Huppertz, 2022; Yusuf, 2023). Thus, bioavailability of nutrients is an important consideration for future studies as micronutrient inadequacy (and consequent deficiency) continues to be of major global concern, especially in vulnerable population groups such as women of reproductive age (Beal, 2024) or people in developing countries (Zhang et al., 2016). Further, "food matrix" and "meal effects" can also influence nutrient bioavailability and associated nutritional/health impacts (McLaren et al., 2021). Ideally, this would be integrated into the scoring system; however, given the lack of available data on this aspect, it remains a topic requiring further research.

Choice of environmental impacts: As mentioned in Section 2.2, climate change was selected as the environmental impact indicator for this current study. However, this is an obvious limitation, particularly as food systems are associated with a wide range of environmental impacts. Future research should include other impact categories of particular significance to food systems, such as biodiversity loss, soil quality, land use change, and water use and pollution.

4.2 Data choices

For any single food item, the environmental impacts may be quite variable. This variability may be due to production practices, different varieties of the same product, seasonality and variable harvest times, packaging type and size, method of storage and length of storage before consumption, distance transported from farm/industry/packhouse gate to the end consumer, and end-of-life management practices. For example, with respect to production practices, tomatoes may be grown in heated greenhouses, passive or unheated greenhouses, or in the open field; eggs can be obtained from chickens in different housing conditions (caged, barn, free range); jam can be made from fresh fruit or from a semi-finished product using any one of three processes – freezing, drying, or via aseptic treatment; honey can be manufactured using stationary or migratory beehives; and salmon can be farmed in land-based/sea-based aquaculture systems or be wild caught (see Supplementary Table 7). The impact scores for these production methods can be markedly different for a food item, e.g., tomatoes grown in an actively heated greenhouse can have a climate change impact score of up to 2.5 kg CO_2 eq./kg compared to 0.3 kg CO_2 eq./kg when grown outside in the open field. Similarly, farmed salmon generally has been reported to have higher impacts (2.2–6.4 kg CO_2 eq./kg salmon) than wild caught salmon (0.8–1.2 kg CO_2 eq./kg salmon).

Production practices can also result in nutritional variability in the same type of food item – for example, farmed salmon contains more PUFAs than wild-caught ones (Colombo and Mazal, 2020). Crop farming systems can also have a significant impact on the nutritional quality of the food. For example, crops grown organically can have different nutrient compositions from conventionally grown crops (Mditshwa et al., 2017). Similarly, Montgomery et al. (2022) showed that crops grown via the regenerative method had increased levels of micronutrients and phytochemicals. The study also found that pork from animals in a regenerative farm had an improved fatty acid profile, including higher levels of omega-3 fatty acids. In addition to production practices, several other factors can impact the nutritional profile of crops, including genotype, climate, soil properties (such as soil pH and organic matter content), geographical factors like elevation, external predatory and disease stressors, as well as post-harvest handling, processing, and storage methods (Hornick, 1992).

In addition to production practices, different varieties of the same product can also have variable environmental impacts. For example, canned pink salmon (one of the toast toppings in this study) is commonly consumed in NZ, but NZ also produces Chinook or King salmon, which is consumed (less commonly) as fresh, hot or cold smoked fillets. The climate change impact of NZ King Salmon was recently calculated at 8.2 kg CO_2 eq./kg edible flesh (thinkstep-ANZ, 2023); this value is 30% higher than the canned pink salmon value used in this study. This could be at least partly due to the production practice-related variability mentioned earlier – NZ King salmon is farmed, whereas the latter is most likely wild caught. For button mushrooms, this study used a climate change impact of 2 kg CO_2 eq./kg mushroom at shed gate. Tongpool and Pongpat (2013) calculated a similar value for shiitake mushrooms, but Ueawiwatsakul et al. (2014) calculated a value of 4 kg CO_2 eq./kg sajor-caju mushrooms at shed gate.

Nutritional content of a food can also vary with seasonality. For example, avocados can remain unharvested longer than other fruits as they ripen only after harvest (Wang et al., 2012). In NZ, avocados are often "left on the tree" to be harvested as per market requirements from September through April. As the fruit's water content decreases, the dry matter increases as the season progresses, leading to increased concentrations for most of the nutrients (see Supplementary Table 8) and changing the nutritional value per serve size.

4.3 Future directions

The current study looked at food items within a single meal context and demonstrated that overall rankings do not change significantly when an expanded index is used in place of a limited one. This finding should be tested by undertaking additional case studies on more diverse samples of simple and/or composite meals.

Regarding application areas, in addition to helping consumers make more informed food choices, the nLCA-based method in this study could also be used to help restauranteurs or catering services to identify nutrition-poor and high environmental impact meals in their menus and change them accordingly to offer more nutritionally and environmentally sustainable options. With respect to home cooked meals, there are several existing websites and apps to help consumers make healthier food choices as per nutritional recommendations (e.g., Avenue et al., 2012; Plate My Meal, 2023; U.S. Department of Agriculture, 2023) as well as those offering a wide range of recipes to help consumers plan and cook meals at home (e.g., All Recipes, 2023). The nLCA method developed in this study could be used to rank meals on existing or new websites and apps, as well as food composition databases and even national food-based dietary guidelines.

Meals can either be home cooked or obtained outside the home from restaurants/cafés, institutional canteens, catered services, or ready meals. In the case of cooked food obtained away from home, or even home delivered meal kits, information about the food items with respect to the variables mentioned in Section 4.1.5 would, in most cases, be available to the service providers (for example, a restaurant would know whether it is sourcing free-range or factory farmed eggs, button or shiitake mushrooms, early or late season avocados, etc.). However, in the case of home-cooked meals based on recipes provided in apps or on websites, it is left to the consumer to source the meal components/ingredients. In this case, the variability mentioned in Section 4.2 can be communicated to the consumer by providing nutritional and environmental score ranges. To this end, it might be useful to investigate the extent of the influence of the abovementioned variables on nLCA-based meal rankings in future studies. This could help streamline the factors which have the largest impacts on individual food items, those which affect majority of the food items, and finally those which influence the nLCA-based meal-level rankings.

With respect to other avenues for future research, weighting the nutrients in a food or meal according to their relative importance (for example, by the average intake of specific nutrients in the target population's diet) is meaningful if directly relevant to the population of interest and should be considered, especially in studies with a focus on specific population groups based on geographical location, age, gender, reproductive status, or socioeconomic variables (Bianchi et al., 2022). For example, regional weighting factors based on nutritional deficiencies/scarcity were applied to nutrient indices in studies conducted in Peru (Avadí and Fréon, 2015), Australia (Ridoutt, 2021) and Sweden (Hallström et al., 2019). Future research might also consider how such nLCA-based meal rankings change when considering the cost of food and affordability, as they have a direct bearing on consumer purchasing decisions (Headey and Alderman, 2019; Hirvonen et al., 2020).

Overall, this study showed that using an expanded nutritional index does not necessarily result in higher NRF scores and also does not alter the final rankings of the toppings in a ToT meal significantly. However, some of the toppings which have high proportions of nutrients not included in the $NRF_{9.3}$ index move up a rank in the baseline scenario (e.g., avocados that are high in MUFAs, and eggs, which contain a large amount of PUFAs, MUFAs, and selenium). Thus, while the $NRF_{9.3}$ index can generally identify the best, medium, and worst performing foods in this meal context, an expanded index could produce more nuanced rankings. More case studies are needed to understand how an expanded index would influence a larger and more diverse range of meals or foods within a meal context. In addition, investigations into the variability of different factors related to assessment of foods and meals (e.g., bioavailability of nutrients, target population nutrient deficiencies, agricultural production practices, seasonality, etc.) can offer more resolution to this nLCA ranking method, which can then be developed further for integration into new or existing tools for improved consumer decision-making. Moreover, although this study takes a primarily consumption-oriented perspective to sustainable nutrition, increased consumer demand for low impact, nutrient-rich meals could also drive systemic change in farming/production practices in the long-term.

Data availability statement

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

Author contributions

ShM: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. SaM: Writing – review & editing, Supervision, Methodology, Conceptualization. JP: Writing – review & editing, Methodology, Conceptualization. CL: Writing – review & editing, Methodology, Conceptualization.

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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

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1363565/full#supplementary-material

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EDITED BY
Antonio Santoro,
University of Florence, Italy

REVIEWED BY
Nawab Khan,
Sichuan Agricultural University, China
Zhong Ren,
Shandong Normal University, China

*CORRESPONDENCE
Meseret Chanie Abate
✉ abatemeseretchanie3407@huse.edu.cn

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Agricultural socialized services and Chinese food security: examining the threshold effect of land tenure change

Baozhong Cai[1], Liao Wangda[2], Fang Shi[3], Meseret Chanie Abate[1]*, Betelhemabraham Geremew[4] and Amsalu K. Addis[5]

[1]Research Institute of Rural Revitalization, Hunan University of Science and Engineering, Hunan, China, [2]College of Economics, Hunan Agricultural University, Changsha, China, [3]School of Humanities and Management, Hunan University of Chinese Medicine, Changsha, China, [4]School of Public Administration, Hunan Agricultural University, Changsha, China, [5]School of Business, Hubei University, Wuhan, China

Revolutionary agricultural structural reforms in the supply chain and cutting-edge institutional mechanisms are pivotal in catalyzing a quantum leap in food production. China's focus on achieving self-sufficiency in grain production for domestic security necessitates structural reforms in the agricultural supply chain and innovative institutional mechanisms. The emergence of socialized agricultural institutions plays a pivotal role in providing essential services to smallholder farmers. However, a dearth of studies evaluating the efficacy of these services in enhancing grain production exists. This study aims to fill this gap by analyzing provincial panel data from China spanning 2011 to 2020 to evaluate the impact of Agricultural Socialized Services (ASS) development levels on grain production. Employing panel and panel threshold models for empirical analysis, the research investigates how this impact varies between major grain-producing regions and non-major grain-producing regions. Findings indicate a significant positive effect of ASS on grain production, with a correlation coefficient of 1.3555. While its impact is less pronounced in grain-producing regions, it proves beneficial in non-grain regions. Moreover, the transfer of farmland use rights amplifies ASS's influence on grain production, with a threshold value of 33.18%. The study concludes by outlining policy implications from various perspectives, providing practical recommendations for policymakers and stakeholders in the agricultural sector.

KEYWORDS

grain yield, agricultural socialized services, farmland use right transfer, threshold effect, land tenure policy

Introduction

Maintaining grain security is a top priority on China's political agenda due to its close link with food security (Niu et al., 2022). To achieve self-sufficiency in grain production and ensure domestic security, the agricultural sector in China prioritizes continuous promotion of structural reform on the supply side and institutional mechanism innovation (Zhan, 2017). Despite these efforts, China faces significant challenges in meeting its growing grain demands, including a rising population and increased demand for animal products. By 2030, China will require 776 million metric tons of grain, a 35.9% increase from its best year on record (Li et al., 2014). Rapid urbanization poses a significant threat to agricultural land availability, leading to low resource efficiency, resource scarcity, declining yield response, competition for non-agricultural land usage, and environmental degradation (Li et al., 2014). In response to these challenges, institutions such as agricultural machinery cooperatives, specialized service organizations, farmer professional cooperatives, and individual service providers provide services to smallholder farmers in the form of agricultural socialized services (ASS). These services have been crucial in bridging the gap between smallholder farmers and modern agriculture, contributing to food security. However, few studies have examined the effectiveness of these services in improving grain production.

As nations globally grapple with the complexities of food security and sustainable agricultural practices, there is an escalating realization of the pivotal role played by agricultural services in bolstering smallholder farmers and enhancing productivity. Leveraging insights from experiences in countries such as India, Brazil, and Thailand, where analogous initiatives have been executed to elevate agricultural productivity and guarantee food security, can furnish invaluable comparative perspectives for small-scale agricultural countries. These nations have delved into diverse models of agricultural services and land tenure reforms to cater to the exigencies of smallholder farmers and amplify food production. In India, for instance, the establishment of farmer producer organizations (FPOs) has wielded a pivotal influence in furnishing collective support and services to small-scale farmers, culminating in enhancements in agricultural productivity and market access (Nayak, 2016). Brazil's encounter with land tenure regularization and agrarian reform programs has underscored the potential advantages of secure land rights in fostering investment and productivity in agriculture (Reydon et al., 2015). Likewise, Thailand's endeavours to foster agricultural cooperatives and extension services have contributed to augmenting farmers' capacities and amplifying food production (Promkhambut et al., 2023). Comprehending how distinct models of socialized agricultural services have impacted food security and agricultural productivity across varied socio-economic and agro-ecological contexts is imperative for informing effective policy decisions and interventions.

Recent studies have underscored the pivotal role of ASS in China, offering smallholder farmers with a necessary path for modern agricultural advancement (Shi et al., 2023). These services serve as a transformative link between conventional small-scale farming practices and cutting-edge agricultural technologies and techniques employed in contemporary agriculture (Huan et al., 2022). By tapping into ASS, smallholder farmers receive access to resources and support that were previously unavailable for their operations (Chen et al., 2023). ASS encompass a diverse array of assistance, including irrigation, pest control, technical guidance, and support for farmers (Hao et al., 2023). These services ultimately enhance productivity and efficiency through the introduction of modern farming methods and technologies. Notably, these services surmount the constraints of small landholdings by consolidating petite plots into larger farms through farmland transfer and consolidation, enabling economies of scale and substantial investment in advanced technologies (Zang et al., 2022). Furthermore, ASS provide access to knowledge-sharing networks and market intelligence, empowering farmers to make informed decisions regarding crop selection, planting schedules, and pricing strategies (Yang et al., 2023). Nonetheless, the mechanism by which ASS affects grain production has not been fully explored.

Currently, there exist three fundamental types of land transfer (Zhou et al., 2021). The first type entails the relinquishment of property rights from village collectives to the State. The second type concerns the transfer of land contractual rights, which was more widespread before the current trend of land transfers. However, it is the third type, the transfer of land management rights that has been the primary catalyst behind the extensive consolidation of land into commercial entities in recent years. This study specifically focuses on the type of land transfer, which is commonly known as land transfer, farmland transfer, farmland use right transfer, or agricultural land transfer in the literature. It is worth noting that this transfer has led to an enormous amount of land being amalgamated into commercial units in recent years.

The transfer of farmland use rights in China represents a critical shift of agricultural land from individual farmers to larger farming entities or agricultural corporations (Ou and Gong, 2021), driven by compelling factors. The urgent demand for agricultural modernization and heightened productivity is a key impetus behind this phenomenon (Ye, 2015; Kuang et al., 2021). The consolidation of small, fragmented plots into more efficient farms facilitates the adoption of cutting-edge farming techniques, cleaner grain production, mechanization, and economies of scale (Zhu et al., 2018; Duan et al., 2021), ultimately bolstering agricultural productivity, strengthening food security, and supporting ongoing rural development efforts.

Moreover, rapid urbanization and infrastructural development have an additional influence on farmland transfer (Wang et al., 2021; You et al., 2021), as burgeoning urban areas demand land for residential, commercial, and industrial purposes, leading to the conversion of agricultural land for non-agricultural uses (Li et al., 2020; Xu et al., 2020). In response to these multifaceted challenges, the Chinese government has enacted policies and regulations to ensure equitable compensation, safeguard farmers' rights, and promote sustainable land management practices during the farmland transfer process (Ma et al., 2020). While the favourable function of farmland use transfer is acknowledged, further research is needed to determine how it improves smallholder farmers' usage of ASS.

Although abundant research has been conducted on the effect of ASS on smallholder farmers' agricultural production, suggesting that it incentivizes the adoption of pro-environmental agricultural practices (Cai et al., 2022; Chen Z. et al., 2022; Cheng et al., 2022; Ren, 2023), increase the demand for large- and middle-sized agricultural machinery and promotes labour transfer among grain producers (Chen T. et al., 2022), and mitigates the negative effects induced by rural labour migration (Wang and Huan, 2023), slight regard has been paid to the effect of land tenure change which causes farmland scale variation on smallholder farmers' accessibility and utilization of services provided by social entities. This study investigates the effect of farmland use right transfer on the ability of smallholder farmers to access ASS in the context of grain production output in China.

The empirical exploration of the interplay between farmland transfer, ASS, and grain yield in China remains notably inadequate. Presently, there exists a dearth of evidence to substantiate the existence of a threshold effect of farmland transfer on the impact of ASS on grain yield. The transfer of farmland has the potential to significantly influence the delivery of ASS, encompassing critical components such as irrigation, pest control, technical support, and various forms of assistance extended to farmers. By consolidating small plots into larger farms, farmland transfer facilitates heightened investment in modern technologies and reaps the benefits of economies of scale (Duan et al., 2021). However, beyond a certain scale, the advantages of farmland transfer may reach a point of saturation or even decline (Fei et al., 2021). This can be primarily attributed to the emergence of coordination challenges and inefficiencies as farms expand in size. The formidable scale of large-scale farming operations may impede the effective provision of ASS (Zang et al., 2022), leading to difficulties in efficiently applying pesticides or fertilizers across extensive areas and potentially diminishing grain yield. Consequently, this could counteract any potential gains derived from consolidation. The optimal scale of farms is depends on various factors, including regional conditions, infrastructure development, and governmental policies (Ren et al., 2019). Striking a balance between farm scale and the availability of socialized services is crucial for maximizing agricultural productivity and ensuring robust food security.

The empirical significance of this study is underscored by its robust methodological approach and revelatory findings. Utilization of the panel threshold model and the formulation of an index evaluation system, this study yields invaluable insights into the dynamic interplay between ASS and grain yield. These empirical contributions will enrich our understanding of the pivotal role played by ASS in strengthening food security and provide pragmatic implications for policymakers and stakeholders in the agricultural sector. From a theoretical perspective, this study contributes to our understanding of the factors influencing the effectiveness of ASS in ensuring food security. By examining the threshold effect of farmland transfer, the study delves deeper into the complex relationship between ASS and grain yield. This analysis will enhance our theoretical comprehension of the mechanisms through which ASS can promote agricultural development and food security. From a practical perspective, this study lies in its policy implications for promoting food security. By providing guidance on how to strengthen the link between ASS, land transfer, and food security, this study offers practical insights for policymakers working towards sustainable agricultural development and improved food security. The aim of this study is threefold: (1) to examine the impact of the development level of ASS on grain production by analysing provincial panel data from China between 2011 and 2020. (2) To explore how this effect varies between the main grain-producing areas and non-main grain-producing areas. (3) To determine whether farmland use right transfer has a threshold effect on the relationship between ASS and grain yield.

Literature review

Improving the inclusivity of agricultural services is crucial for ensuring sustainability, as it provides small and socio-economically marginalized farmers with equal access to the knowledge and resources needed for adopting advanced agricultural practices and securing thriving livelihoods, irrespective of factors such as landholding, gender, age, or caste (Dogan and Adanacioglu, 2024; Sahu et al., 2024). The frequency of agricultural extension visits and the application of participatory approaches in extension services are key factors in explaining variations in technical efficiency among grain producers, which in turn can help bridge identified efficiency gaps (Djuraeva et al., 2023). This growing body of research is dedicated to exploring the nexus between agricultural services and grain yield specifically within the context of smallholder farmers.

Previous literature on grain yield in China focuses on several key topics. Firstly, there is a strong emphasis on grain production technology and innovation (Zhang D. et al., 2021; Zhang S. et al., 2021; Deng et al., 2022). This includes studying new crop varieties, irrigation techniques, fertilizers, and pest control measures to enhance grain yields. Secondly, there is a substantial attention to agricultural policies and subsidies to evaluate their impact on grain production (Song et al., 2021; Bai et al., 2022; Fan et al., 2023). This entails evaluating the role of government policies, price support mechanisms, land use policies, and agricultural input subsidies. Thirdly, there is a notable stress on land use and management, with researchers looking into the consequences of land fragmentation, land use patterns, and the benefits of land consolidation, mechanization, and scale management (Verburg et al., 2000; Wang et al., 2020; Xie et al., 2020; Ma et al., 2023). Fourthly, the pronounced emphasis on the impact of climate change and variability on grain yields is also a significant research focus, with efforts underway to identify adaptation strategies (Alexandrov and Hoogenboom, 2000; Kukal and Irmak, 2018; Bento et al., 2021; Habib-ur-Rahman et al., 2022; Hasegawa et al., 2022). Fifthly, some scholars also explore the relationship between grain yields and rural development, poverty reduction, and the role of rural infrastructure, education, and health in improving productivity (Wang et al., 2015; Ge et al., 2018). Finally, market access and international trade are examined to understand the effects on domestic grain prices and production (Chan, 2022; Falsetti et al., 2022). This study examines the impact of the development level of ASS on grain production by analysing provincial panel data from China between 2011 and 2020, an area that has received little attention in previous research.

ASS have become an important tool for promoting sustainable agriculture, involving the provision of agricultural services to smallholders through collective action and shared resources. One impact of ASS is their potential to promote sustainable agricultural technology among smallholders, hence supporting the transition from conventional to sustainable agriculture (Huan et al., 2022). Additionally, these services improve collective action for the governance of irrigation commons, mitigating the negative effects of rural labour migration (Wang and Huan, 2023). Farmers who receive ASS are more likely to adopt sustainable practices such as using organic fertilizers and soil testing (Shi et al., 2023).

Increased ASS encourage small farmers to transfer more farmland, incentivize the adoption of soil testing and straw returning technology among farmers, leading to improved cultivated land quality protection (Cai et al., 2022; Cheng et al., 2022). Household characteristics, biophysical conditions, community attributes, and rules-in-use jointly generate the action situation in the process of smallholders' cooperative utilization of ASS (Zang et al., 2022). Furthermore, ASS positively influences farmers' behavior regarding the application of organic fertilizer, while also reducing the intensity of agricultural carbon emissions (Chen T. et al., 2022; Ren, 2023). These services can provide essential support, production, operational, financial, and distribution services for the agricultural production chain, significantly reducing the intensity of agricultural carbon emissions (Chen Z. et al., 2022). They can also boost demand for large- and middle-sized agricultural machinery and facilitate labour transfer among maize farmers (Chen T. et al., 2022; Yang and Li, 2022). In general, ASS have been found to positively impact on various aspects of agricultural practices and outcomes. These include promoting sustainable agriculture, encouraging collective action, reducing negative impacts of rural labour migration, adopting sustainable agricultural practices, transferring more farmland, improving land quality protection, incentivizing organic fertilizer application, reducing carbon emissions intensity, and promoting labour transfer (Chen T. et al., 2022; Chen Z. et al., 2022; Yang and Li, 2022; Ren, 2023). Further research is necessary to identify best practices for implementing ASS in different contexts and better understand their mechanisms of impact.

Incidentally, scholars have examined various aspects of the relationship between farmland and grain yield. This includes changes in land distribution, usage patterns, consolidation, and the effects of land tenure and management practices (Ge et al., 2018; Wang et al., 2019; Duan et al., 2021). The role of technological advancements (Tong et al., 2023), environmental factors (Ma et al., 2022), policy interventions (Yu and Wu, 2018), and socio-economic factors (Arhin et al., 2023), are also explored. For instance, Ge et al. (2018) highlight the importance of regulating the farmland transition process as it provides a basis for decision-making regarding appropriate grain production scales for farmers. Another factor influencing grain production is the subsidy payments for contracted farmland. Zhang D. et al. (2021) find that a 10% increase in grain subsidy payments leads to a 1% increase in farmland rental prices. Ultimately, the goal is to provide insights into this complex relationship to support sustainable agricultural practices.

In terms of farmland quantity, Li et al. (2023) observed that, despite a decline in farmland in China's major grain-producing regions, grain production has increased. This is due to the decoupling of grain production from farmland quantity, especially in central-eastern China. They emphasize the need for sustainable decoupling to guarantee food security without compromising ecological security. Additionally, Liu et al. (2018) discovered that households renting land often cultivate larger quantities of grain. The amount of land rented positively correlates with the amount of grain planted. However, their study did not find a significant impact on grain acreage in relation to farmland rental. Qiu et al. (2020), on the other hand, focused on the impact of land renting-in on grain acreage, finding that land renting-in has a positive effect on grain acreage, particularly in situations where agricultural labour is limited. This effect is achieved as lessees increase machinery utilization in rice production. However, some argues that this increase in machinery usage does not extend to cash crops, as mechanization is more feasible for grain crops in rural China (Huo et al., 2022), while others disagree regarding agricultural production (Peng et al., 2022).

The establishment of nature reserves also has implications for grain production. Chen T. et al. (2022) found that nature reserves reduce average grain production, with a greater impact in high-yield areas. These reserves also decrease both grain yield and the area of cultivated farmland in counties where they are implemented. Similarly, land factors have a substantial effect on grain production dynamics in China, as highlighted by Pan et al. (2020). They emphasize the importance of considering land-related factors when analysing and planning for grain production. Additionally, the spatial mismatch between grain production and farmland resources is a significant challenge in China. For instance, Li et al. (2017) highlight various factors contributing to this mismatch, including regional structure imbalances, ecological risks, agricultural production risks, and the volatility of food prices. Addressing this spatial mismatch is crucial to mitigate the decline in grain yield caused by these imbalances, which this study aims to investigate through empirical analysis of the nexus between ASS and grain yield. Furthermore, Zhu et al. (2022) explore the relationship between farm size and fertilizer use efficiency. They found that larger farm sizes positively affect fertilizer use efficiency. This is not due to an increase in grain yield, but rather through a reduction in fertilizer use while maintaining the grain yield at a relatively constant. In conclusion, the relationship between farmland and grain yield in China is complex, influenced by various factors such as farmland rental, land factors, fertilizer utilization, farm size, nature reserves, and spatial mismatch. Understanding these dynamics is essential for policymakers to make informed decisions regarding grain production and ensure food security while considering ecological and economic sustainability.

Theoretical framework

The influence of ASS on grain production can be observed from two perspectives. Firstly, it involves the input of various factors, including labor, land, and materials. Secondly, it encompasses technology investment, as service organizations can assist small farmers in adopting advanced technologies to enhance their agricultural production processes and improve overall efficiency. Building upon this understanding, this article aims to analyze the impact of ASS on grain yield by constructing a growth accounting model and adopting the Cobb Douglas production function.

$$Y = A\text{Labor}^{\beta_1}\text{Land}^{\beta_2}\text{Material}^{\beta_3} \tag{1}$$

Where: Y, represents grain yield, A, represents technological progress, Labor, represents the input of labor, Land, represents the input of land factors, and Material, represents the input of material factors.

$$X = f_x(\text{ASS}) \tag{2}$$

$$X = A, \text{Labor}, \text{Land}, \text{Material} \tag{3}$$

$$\begin{aligned}\frac{dY}{Y} = \frac{1}{A}\frac{\partial f_A(\text{ASS})}{\partial ASS}d\text{ASS} + \frac{\beta_1}{\text{Labor}}\frac{\partial f_{\text{Labor}}(\text{ASS})}{\partial ASS}d\text{ASS} \\ + \frac{\beta_2}{\text{Land}}\frac{\partial f_{\text{Land}}(\text{AS})}{\partial AS}d\text{ASS} + \frac{\beta_3}{\text{Material}}\frac{\partial f_{\text{Material}}(\text{AS})}{\partial AS}d\text{ASS}\end{aligned} \tag{4}$$

The Equations 1–4 highlight that changes in grain output are attributed to modifications in labor factors, land factors, material factors, and technological progress. Additionally, the development of ASS contributes to increasing grain production through its impact on factor inputs and technological advancements.

The rural labor force in China has been shrinking as a result of workers to urban areas, raising concerns about its impact on grain output. Despite this tendency, China's grain production has remained consistent at 1.3 trillion pounds for seven years in a row (Global Times, 2021), demonstrating that labor transfer has had little impact on grain production. This begs the question of what factors contribute to a rise rather than a reduction in agricultural output. From a demand perspective, an aging population and part-time employment of the rural labor force have generated a pressing need for ASS among many farmers. These services handle labor shortages, relieve issues associated with substantial land management or land abandonment, and maintain food security. From a supply perspective, ASS act as a conduit for human capital and intellectual capital, successfully alleviating labor constraints in agricultural operations and compensating for labor shortages. This substitution effect significantly reduces the farmers' labor intensity, boosts their enthusiasm for large-scale operations, and ultimately leads to increased food output (Liao et al., 2019; Yang and Li, 2022).

Small-scale farming has been the predominant agricultural model in China, characterized by low productivity levels, weak resistance to natural disasters, and high production costs. Arable land fragmentation leads to high cultivation costs and low profits, while the decentralization of operations incurs high organizational, coordination, and management costs. This hinders the development of rural public infrastructure and the sustainability of production and life. The innovative development of ASS can assist small farmers in centralizing land transfers, achieving moderate-scale operations in agriculture. The integration of land resources can enhance the quality of arable land, thereby increasing food output (Ren et al., 2019; Cai et al., 2022; Huan et al., 2022; Shi et al., 2023).

The development of ASS plays an essential role in concentrating and integrating agricultural production materials within a certain range, enabling more effective and environmentally friendly production activities. This includes the incorporation of green production factors, utilizing organic fertilizers and low-toxicity pesticides to promote sustainable and environmentally friendly agricultural development. Additionally, the integration of agricultural production materials with scientific and technological research and development resources is crucial, leading to sustained growth in food production. ASS not only enhance overall agricultural productivity but also attract high-quality capital and technical expertise, optimizing resource allocation and driving improvements in the quality of grain production (Huan et al., 2022; Zang et al., 2022; Shi et al., 2023).

ASS contribute to increased utilization of agricultural technology and equipment, reducing production costs and improving efficiency. Furthermore, these services facilitate the upgrading and modernization of agricultural machinery, guiding farmers in adopting advanced agricultural technology. By providing socialized services related to agricultural machinery, ASS help alleviate the need for farmers to purchase expensive production materials and tools, thereby improving overall productivity in the food production process (Chen T. et al., 2022).

ASS play a pivotal role in empowering farmers with essential knowledge and skills related to crop management, pest control, and soil conservation. Beyond knowledge transfer, ASS also grant farmers access to critical resources including irrigation facilities, fertilizers, and modern machinery, thereby enhancing their agricultural practices. This comprehensive support system provided by ASS contributes significantly to the improvement of grain yield among farmers. However, the impact of ASS on grain yield is influenced by factors such as farmland transfer dynamics and the resilience of rural communities. Figure 1 illustrates the intricate relationship between ASS, farmland transfer processes, and ultimately, the resulting grain yield outcomes. Understanding and optimizing this interplay is vital for sustainable agricultural development and enhanced productivity in rural.

Data sources and methodology

Data sources

The panel data used in this study were collected from various sources from 2011 to 2020. As depicted in Table 1, data on grain yield, agricultural socialized services, agricultural structure coefficient, and farmland use transfer were obtained from China's Rural Statistics Yearbook (CRSY). Data on urbanization rate and openness to the outside world were derived from the National Bureau of Statistics (NBS), while data on the primary industry were extracted from China's National Statistics Yearbook (CNSY).

Due to data availability constraints, this study excluded Tibet, Hong Kong, Macao, and Taiwan as research areas, leaving a total of 30 provinces, cities, and autonomous regions in mainland China. Based on the research conducted by Yu et al. (2019), the primary regions responsible for grain production in China consist of 13 provinces and autonomous regions, namely Shandong, Jiangsu, Anhui, Jiangxi, Liaoning, Heilongjiang, Jilin, Hebei, Inner Mongolia, Henan, Hubei, Hunan, and Sichuan (see Figure 2).

Dependent variable

The dependent variable in this context is the level of grain yield (GP). Grain yield refers to the amount of grain produced in a given area or region. It is an important measure of agricultural productivity, as it reflects the efficiency of crop production and the capacity of a region to meet its food needs. To measure the level of grain yield, the study uses the total grain production level of each region. This measure reflects the actual quantity of grain produced in a particular region, taking into account the different types of grains and their respective yields. The study aims to capture the overall grain yield performance of each region, providing insights into potential factors that may affect this performance, such as ASS level and changes in farmland tenure.

Independent variable

The primary objective of this study is to investigate the direct impact of ASS on grain yield, as well as its indirect influence through farmland transfer as a threshold effect. Thus, the core independent variable being examined is the level of ASS. This concept builds upon the research of scholars, such as Shi et al. (2023) and incorporates further innovation. To assess ASS, an evaluation index system has been developed based on five key dimensions: agricultural means of production services, agricultural infrastructure services, rural science and technology and information services, agricultural financial services, and rural public services. Each dimension consists of a set of sub-services, resulting in a total of 19 evaluation indicators. It is important to note that all these indicators are positive indicators, implying that higher scores indicate better performance in each dimension. Refer to Table 2 for a detailed breakdown of these indicators. The establishment of this evaluation index system allows

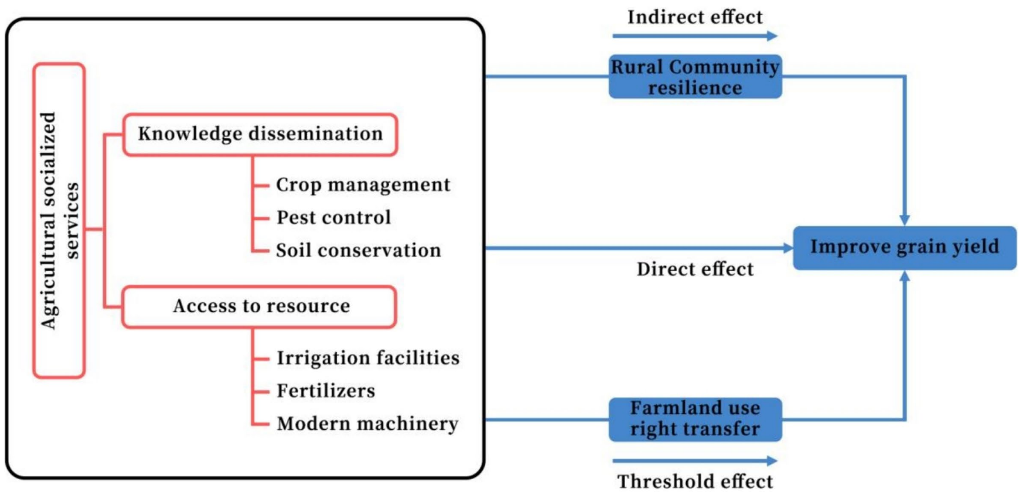

FIGURE 1
Theoretical framework connecting agricultural socialized services and farmland use right transfer to grain yield. Source: authors' conceptualization.

TABLE 1 Variables and data sources.

Denote	Variables	Measurement	Data source
Dependent variable			
GD	Grain yield	The total grain production level of each region	CRSY
Independent variable			
ASS	Agricultural socialized services	Based on the evaluation index system for agricultural socialized services	CRSY
Control variables			
UR	Urbanization ratio	The proportion of urban population to the total population	NBS
TR	Extent of trade openness ratio to the outside world	The ratio of total import and export volume to regional GDP	CRSY
IN	Primary industry	The ratio of the output value of the primary industry to the regional GDP	CNSY
AI	Agricultural structure coefficient	The ratio of grain planting area to total crop planting area is used	CRSY
Threshold variable			
FT	Farmland use right transfer	The ratio of the area of transferred land to the area of contracted land	CRSY

for a comprehensive assessment of the various aspects of ASS, providing valuable insights for policymakers and researchers to analyze and improve the overall effectiveness of these services in supporting agricultural development and rural well-being.

Based on the evaluation index system, the first step is to standardize each of the indicators. This standardization process ensures that all indicators are transformed to a common scale, allowing for meaningful comparisons between them. After standardization, the next step involves calculating the weight of each indicator using the entropy method. This mathematical approach assesses the relative importance or contribution of each indicator to the overall evaluation. The equation is:

$$Z_{ij} = \sum w_j x_{ij} \quad (5)$$

In Equation 5, the variable w_j represents the weight assigned to each indicator. The standardized value of each indicator is denoted by x_{ij}. This standardization process ensures that all indicators are transformed to a common scale, allowing for meaningful comparisons and aggregations. By standardizing the values, variations in measurement units and scales are eliminated, enabling a fair and consistent evaluation across different indicators. It accounts for the dispersion and distribution of values across the indicators. Once the weights of all the indicators are determined using the entropy method, the ASS development index can be calculated. This index serves as a comprehensive measure of the overall performance and development level of ASS.

Control variables

Based on the previously mentioned framework analysis, this study identified key factors that significantly influence grain yield. These factors encompass urbanization rate, extent of openness to the outside world, the proportion of the primary industry, agricultural structure coefficient.

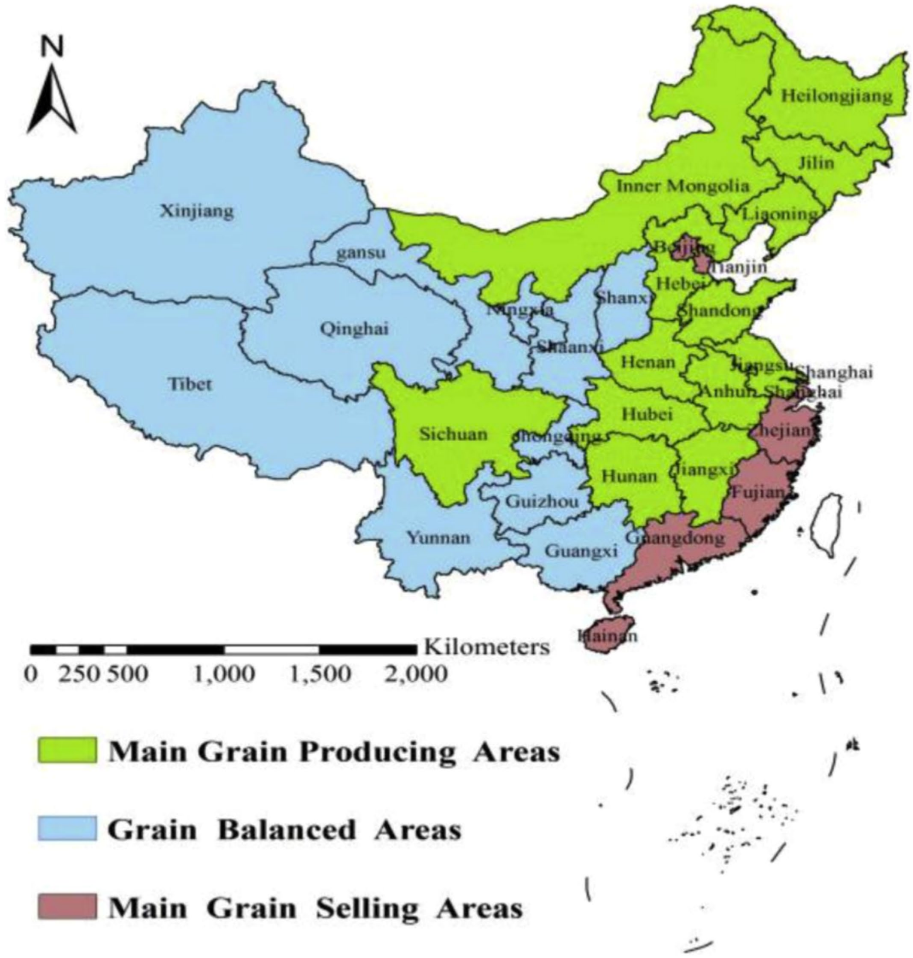

FIGURE 2
Classification of regions based on the proportion of grain production in China. Source: adopted from Yu et al. (2019).

Urbanization rate: The impact of urbanization on grain yield can be understood through two main factors (Shen et al., 2024). Firstly, urbanization typically leads to a reduction in available arable land area, directly contributing to decreased grain production capacity. However, urbanization also has indirect effects on grain yield. As urban areas expand, there is a concentration of population and growth in non-agricultural sectors. This agglomeration and economic diversification can influence the input factors and scale structure of grain production. For example, the increased demand for food in urban areas may drive technological advancements and investment in agricultural practices, leading to improved productivity and efficiency in grain production. Secondly, urbanization often brings about changes in land use patterns, with a shift towards more intensive and specialized farming practices. This shift can lead to higher yields per unit of land, compensating for the reduction in overall arable land area.

The extent of openness to the outside world: It can have a significant impact on grain yield. This is measured by the trade openness ratio (TR), which represents the ratio of total import and export volume to regional GDP. A higher level of trade openness indicates increased imports of agricultural products, which can potentially affect domestic grain production (Hu et al., 2024). When a region becomes more open to foreign markets, it may rely more on imported agricultural products, including grains, rather than producing them domestically. This shift towards reliance on imports may result in a decline in domestic grain production.

The proportion of the primary industry. A higher proportion of the primary industry, particularly agriculture, generally leads to increased food production. This is because a greater focus on agricultural activities can result in more resources and investments being allocated to the industry, leading to improved productivity and efficiency in grain production (Zhang et al., 2022). However, there are potential challenges associated with a high proportion of the primary industry. The development of high-end industries may attract rural labour away from agriculture, leading to a decrease in the number of full-time farmers. This shift in labour allocation may have an influence on the availability of skilled agricultural workers and potentially affect grain production. An upgraded industrial structure, on the other hand, may provide advanced technologies and abundant resources to the agricultural sector. This integration of advanced technology and resources from other industries into agriculture can contribute to

TABLE 2 Evaluation index system for ASS.

Sub-item	Specific indicators	Indicator calculation method	Indicator attribute
Service level of agricultural means of production	Usage of agricultural plastic film	Agricultural plastic film usage (tons)	+
	Fertilizer supply	Chemical fertilizer conversion rate	+
	Pesticide supply	Pesticide usage	+
	Agricultural machinery supply	Total power of agricultural machinery	+
	Agricultural production price index	Agricultural Production Price Index	+
Agricultural infrastructure service level	Water infrastructure	Effective irrigation area (1,000 hectares)	+
	Electricity infrastructure	Rural electricity consumption (100 million kilowatt hours)	+
	transport infrastructure	Highway mileage (10,000 kilometers)	+
Rural science and technology informatization service level	Rural internet application level	Rural broadband access users (10,000 households)	+
	Rural mobile phone usage level	Number of mobile phones owned by rural residents per hundred households at the end of the year (unit)	+
	Rural computer usage level	Home computer ownership	+
Agricultural finance and insurance service level	Agricultural insurance premium level	Agricultural insurance premium income (million)	+
	Development level of agricultural loans	Balance of agricultural loans (100 million yuan)	+
	Compensation level of agricultural insurance	Agricultural insurance compensation expenses (million)	+
Rural public service level	Financial support for agriculture expenditure	Local fiscal expenditure on agriculture, forestry, and water resources (100 million yuan)	+
	Development level of logistics services	Rural delivery routes (kilometers)	+
	Soil erosion control level	Soil erosion control area (1,000 hectares)	+
	Reservoir construction level	Number of reservoirs	+
	Prevention and control level of agricultural natural disasters	1-Disaster rate	+

innovation, improved farming practices, and ultimately enhance grain yield.

Agricultural structure coefficient. It indicates a larger proportion of land dedicated to grain cultivation. Allocating more land resources to growing grains can directly contribute to increased grain output. This is because an increased grain planting area allows for greater cultivation and production of grains, leading to higher yields. Managing and controlling the agricultural structure coefficient is crucial in promoting increased grain yield (Yu et al., 2021). Optimizing the allocation of land resources and ensuring a higher proportion of land is devoted to grain cultivation can enhance agricultural productivity. Taking into account and controlling variables such as the availability of land resources, this study aims to explore the influences of these factors on grain production and yield.

Threshold variable

This study aims to determine whether farmland use right transfer has a threshold effect on the relationship between ASS and grain yield (Ding et al., 2024). The transfer of farmland is selected as a threshold variable to explore the non-linear relationship between ASS and grain yield increase. This threshold can significantly influence the efficiency of ASS scale operations and their effectiveness in increasing total grain yield. When the rate of agricultural land transfer surpasses a certain threshold, it positively impacts the relationship between ASS and grain yield. An increased rate of land transfer can lead to larger-scale agricultural operations, resulting in improved efficiency, access to modern technology, and the utilization of advanced farming techniques. These factors can ultimately contribute to increased grain yield. However, it is important to note that there may be a threshold beyond which further increases in the rate of land transfer could result in diminishing returns or even negative effects on grain yield. This may be due to issues such as land fragmentation, lack of skills and expertise, or inadequate management of large-scale operations.

Methodology

This empirical study examines the impact of ASS on grain yield while considering regional differences. However, measuring ASS in a specific region may result in selection bias due to the complexity of ASS, which arises from diverse and interconnected factors that support agricultural production, rural development, and the well-being of farmers. The complexity arises from the involvement of multiple stakeholders, including government agencies, financial institutions, technology providers, extension services, and rural communities. Managing this complexity requires a holistic approach, coordination among different actors, adaptive strategies, and continuous monitoring and evaluation to ensure the effectiveness and efficiency of services in supporting sustainable agricultural development. To address selection bias, this study developed an evaluation index system for ASS (see Table 2).

The study also developed a linear panel data model to verify the impact of the development level of ASS on grain yield. Ample evidence exists on the role of panel regression model in analyzing data that involves both cross-sectional and time-series dimensions (Arellano and Bond, 1991). This model provides a robust framework for accounting for individual heterogeneity, capturing time-specific effects, increasing efficiency and statistical power, handling endogeneity, and exploring dynamics and causal relationships. The linear panel data model is commonly used to examine the linear relationship between dependent and independent variables while accounting for individual heterogeneity and time-specific effects. In this model, the relationship can be expressed as follows:

$$Y_{it} = \beta X_{it} + \mu_i + \varepsilon_{it} \tag{6}$$

In Equation 6, Y represents the dependent variable for individual i at time t. X_{it} represents the vector of independent variables for individual i at time t. β represents the coefficients associated with the independent variables, μ_i represents individual-specific effects that are constant over time, and ε_{it} represents the error term.

The specific form of a linear panel data model for this study constructed as follows.

$$GP_{it} = \beta_0 + \beta_1 ASS_{it} + \beta_2 M_{it} + \varepsilon_{it} \tag{7}$$

In Equation 7, i refers to the province and t indicates the year. The dependent variable GP represents grain yield. The independent variable ASS represents the development level of socialized agricultural services. M represents control variables, while the term ε denotes the random error term. To examine the non-linear association between the independent variable (ASS) and the dependent variable (GP), this study used farmland use right transfer as the threshold variable. Thus, the study employed the most commonly used panel threshold model developed by Hansen (1999), as it is useful to explore the relationship between dependent and independent variables in panel data (Yi and Xiao-li, 2018; Miao et al., 2020). Particularly, it is essential when there is a non-linear relationship between the variables such that the relationship changes abruptly at a certain point or threshold value of the independent variable. The fundamental equation is:

$$Y_{it} = u_i \beta_1 X_{it} I(q_{it} \le \gamma) + \beta_2 X_{it} I(q_{it} > \gamma) + \varepsilon_{it} \tag{8}$$

Where, i represents the province, t represents the year, q_{it} represents the threshold variable, γ stands for the threshold value to be estimated, and ε_{it} signifies the random error. The individual intercept u_i denotes the fixed effect and $I(q_{it} > \gamma)$ signify the indicative function. If the condition inside the parentheses holds true, the function takes the value of 1; otherwise, 0. By drawing on Equation (8) and consulting the available literature, the study formulated the threshold panel model for assessing how the services provided by social organization affect grain production output, with farmland transfer serving as the threshold variable.

TABLE 3 Descriptive statistics of the main variables.

Variables	Mean	SD	Min	Max	Observations
GP	0.21	0.18	0.002	0.76	300
ASS	0.25	0.13	0.04	0.56	300
UR	0.57	0.12	0.38	0.88	300
TR	0.27	0.31	0.01	1.53	300
IN	0.09.	0.05	0.00	0.26	300
AI	0.66	0.14	0.36	0.97	300
FT	0.33	0.17	0.03	0.92	300

$$GP_{it} = \alpha_1 ASS_{it} I(FT_{it} \le \gamma) + \alpha_2 ASS_{it} I(FT_{it} > \gamma) + \alpha_3 M_{it} + \mu_{it} \tag{9}$$

In Equation 9, the threshold value is denoted by γ, while the control variable is represented by M. The threshold variable, which plays a significant role, is farmland transfer (FT). α1, α2, and α3 are the coefficients to be estimated. ε_{it} is the error term representing unobserved factors.

Results

Descriptive statistics

Table 3 shows the results of the descriptive statistics. The mean grain yield is 0.21 with a standard deviation of 0.18, indicating that grain production varies moderately across the sample. For the ASS, the study developed an index evaluation system to fully understand the development level of these services in each region. The average level of ASS is 0.25, suggesting that such services are neither scarce nor uncommon. The standard deviation of 0.13 indicates that although the average level is 0.25, there is variability around this average. This implies that in some cases, the level of ASS may be significantly higher or lower than the average in different regions.

The average urbanization rate of 0.57 reflects that, on average, approximately 57% of the population in the studied areas is concentrated in urban regions. With a standard deviation of 0.12, there is considerable variation in urbanization rates among the observations, signifying that certain areas exhibit markedly higher or lower levels of urbanization compared to the average. The observed urbanization rates, ranging from 0.38 to 0.88, vividly illustrates the diversity within the dataset, showcasing instances of modest urban development alongside areas with significantly advanced urban landscapes. These statistical insights provide researchers a through overview of the urbanization context under scrutiny, thereby facilitating the contextualization of the interplay between urbanization and grain yield, as well as its potential correlation with other pertinent variables. The mean extent of trade openness to the outside world being 0.27 suggests that, on average, the areas under study exhibit a moderate level of engagement with external entities and global influences. However, the relatively large standard deviation of 0.31 indicates a wide range of variability in the extent of trade openness across the 300 observations. This implies that some areas have a significantly higher degree of increased imports of agricultural products, which can potentially affect domestic grain production, while others have a substantially lower level.

The proportion of the primary industry is 0.09, with a standard deviation of 0.05, meaning that, across the studied areas, the primary industry, which includes activities like agriculture, forestry, fishing, and mining, contributes to approximately 9% of the regional GDP on average. This suggests that the primary industry plays a relatively modest role in the overall economic output of the areas under consideration. The mean agricultural structure coefficient is 0.66, with a standard deviation of 0.14, indicating that the ratio of grain planting area to total crop planting area is relatively high across the studied areas. This suggests that a significant proportion of the total crop planting area is dedicated to grain cultivation, reflecting a substantial focus on grain production within the agricultural structure. The statistics on farmland use right transfer provide important insights into grain yield. The mean value of farmland use right transfer is 0.33, indicating that 33% of the grain cultivated land is transferred. This demonstrates a moderate level of transfer activity for farmland use rights across the studied areas, suggesting some degree of movement in the right to use farmland within grain production. This implies that there is a degree of activity in transferring the rights to use farmland from one party to another within the grain production.

Empirical results

Table 4 provides an overview of the ASS development index in China and its 30 provinces from 2011 to 2020. The index demonstrates substantial growth in China's overall ASS development, with the average level increasing from 0.223 during 2011–2015 to 0.27 during 2016–2020.

Regional disparities in China lead to varying levels of ASS development among provinces, influenced by resource endowments. Among others, 14 provinces have a higher development level of ASS compared to the national average. In descending order, they are, include Shandong, Jiangsu, Henan, Guangdong, Hunan, Hebei, Sichuan, Anhui, Hubei, Zhejiang, Heilongjiang, Jiangxi, Yunnan, and Inner Mongolia. These regions are predominantly situated in the country's principal grain-producing areas and coastal provinces with well-developed agricultural machinery manufacturing. Notably, provinces such as Guangdong exhibit high levels of agricultural science and technology, contributing to the development of ASS through scientific innovation. Similarly, Heilongjiang, with its large land area and substantial grain production, provides a significant market for ASS. This underscores the importance of both production supply capacity and market demand in driving the development of the ASS market.

Conversely, there are 14 provinces where the development level of ASS is lower than the national average. In descending order, they are, Xinjiang, Guangxi, Liaoning, Fujian, Gansu, Shaanxi, Jilin, Guizhou, Shanxi, Chongqing, Shanghai, Beijing, Hainan, Ningxia, Tianjin, and Qinghai. These regions consist of economically developed areas where the secondary and tertiary industries play a significant role in the economy, such as Tianjin, Beijing, and Shanghai. They also include less economically developed provinces in central and western regions, for instance, Qinghai, Ningxia, and Shanghai. Additionally, provinces with challenging geographical landscapes, like mountainous and hilly areas, face difficulties in implementing large-scale ASS, for instance, Hainan and Fujian.

TABLE 4 The development level of ASS in different provinces from 2011 to 2020.

Area (provinces)	Agricultural socialization service index (provinces above the national average)			Area (provinces)	Agricultural socialization service index (provinces below the national average)		
	2011–2015	2016–2020	2011–2020		2011–2015	2016–2020	2011–2020
Beijing	0.088	0.106	0.097	Hubei	0.306	0.360	0.333
Tianjin	0.061	0.065	0.064	Hunan	0.349	0.422	0.385
Hebei	0.361	0.399	0.380	Guangdong	0.373	0.434	0.403
Shanxi	0.170	0.190	0.179	Guangxi	0.198	0.263	0.231
Inner Mongolia	0.227	0.281	0.254	Hainan	0.071	0.091	0.081
Liaoning	0.220	0.236	0.228	Chongqing	0.126	0.161	0.143
Jilin	0.173	0.203	0.188	Sichuan	0.327	0.425	0.376
Heilongjiang	0.253	0.316	0.285	Guizhou	0.145	0.215	0.180
Shanghai	0.110	0.157	0.131	Yunnan	0.246	0.309	0.278
Jiangsu	0.426	0.500	0.463	Shaanxi	0.177	0.206	0.192
Zhejiang	0.306	0.358	0.332	Gansu	0.188	0.223	0.206
Anhui	0.300	0.366	0.333	Qinghai	0.048	0.074	0.061
Fujian	0.204	0.247	0.225	Ningxia	0.061	0.080	0.071
Jiangxi	0.260	0.302	0.281	Xinjiang	0.205	0.279	0.242
Shandong	0.502	0.541	0.522	Nationwide	0.223	0.270	0.247
Henan	0.410	0.481	0.445				

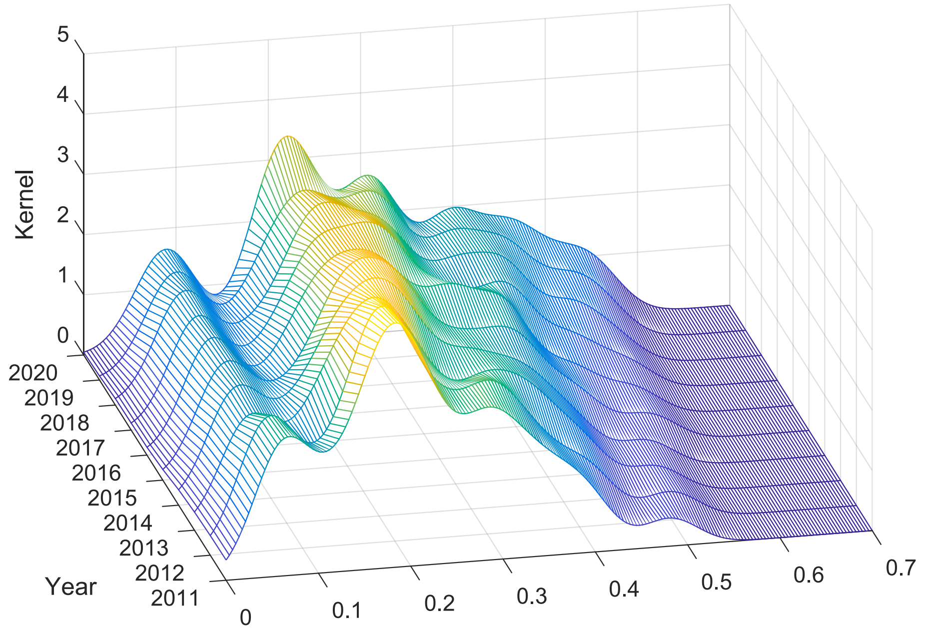

FIGURE 3
Kernel density estimation.

TABLE 5 Results of unit root test.

Variable	LLC	*p* value
GP	−12.2765***	0.0000
AS	−5.4498***	0.0000
UR	−2.9556***	0.0000
TR	−14.3457***	0.0000
IN	−64663***	0.0000
AI	−29.0224 ***	0.0000
FT	−10.8181***	0.0090

*, **, *** stands for 10, 5 and 1% significant level, respectively.

Furthermore, the study conducted kernel density graph analysis to show that the development of China's ASS reveals several noteworthy trends, as depicted in Figure 3. The kernel density graph effectively illustrates the evolving landscape of ASS in China. It highlights the overall progress made while shedding light on the persisting challenges associated with regional disparities in development. There is a clear rightward shift in the main peak, indicating a gradual increase in the level of ASS in China over time. Additionally, the height of the main peak is decreasing while its width is expanding. This suggests that the level of ASS is becoming more dispersed across different regions, with entities operating within this sector are working to bridge the development gap between regions. Moreover, the distributional ductility exhibits a trailing pattern to the right, reaffirming the substantial disparities in the development levels of China's ASS. The persistence of this phenomenon emphasizes the prominent issue of unbalanced development among regions.

Incidentally, to prevent spurious regression due to data instability, unit root tests are performed prior to conducting empirical analysis. Commonly used unit root tests include the LLC test, IPS test, Fisher test, and HT test. In this study, the most widely employed LLC test is utilized (Westerlund, 2009). The results in Table 5 indicate that all variables reject the null hypothesis of non-stationarity. This implies that there is no presence of spurious regression when the data is stationary.

Additionally, the results of the panel data regression for the three models are presented in Table 6, and the Hausman test indicates that the null hypothesis should be rejected at a significance level of 1%, suggesting that fixed effects should be used for analysis. Model (1) in Table 6 is the benchmark regression without any control variables. The results show that the level of ASS has a significantly positive impact on grain yield, as evidenced by the coefficient of 0.9172, which is significant at the 10% significance level. This finding suggests that an increase in the level of ASS can lead to a higher level of grain yield.

In Model (2), control variables have been incorporated into the regression analysis. The results reveal that the coefficient for the relationship between the level of ASS and the total grain yield is 1.3555, which is significantly positive at the 1% significance level. This finding supports the notion that ASS can indeed have a positive impact on grain production, even after accounting for other variables that may influence grain yield. The panel data regression results suggest that increasing the level of ASS is associated with increased grain production. The inclusion of control variables to the analysis further strengthens this conclusion by demonstrating the robustness of the relationship between ASS and grain yield, even when considering other potential factors that could influence grain production.

The analysis, considering the control variables, reveals several significant positive correlations between various factors and grain yield. There is a significant positive correlation exists between the level of urbanization and grain yield, as indicated by the coefficient of 1.1870. This suggests that despite urbanization may reduce rural labour, the infusion of production inputs and adjustments in

TABLE 6 Results of panel data regression analysis.

Variable	Model (1)	Model (2)	Model (3)
	Grain yield		
Agricultural socialized service level	0.9172* (1.83)	1.3555*** (3.97)	1.9887*** (4.51)
Urbanization rate		1.1870*** (2.88)	1.2018*** (2.63)
Extent of trade openness to the outside world		0.6427*** (6.25)	0.5728*** (5.46)
Proportion of primary industry		2.4062*** (4.32)	2.7654*** (4.54)
Agricultural structure coefficient		2.6091*** (11.05)	2.8024*** (11.06)
Constant term	6.8832*** (63.08)	3.9755*** (15.39)	3.6953*** (12.36)
N	300	300	270
Time	Regular	Regular	Regular
Area	Regular	Regular	Regular

*, **, *** stands for 10, 5 and 1% significant level, respectively.

TABLE 7 Result of sub-sample regression.

	Model (4)	Model (5)
	Main grain producing areas	Non-main grain producing areas
Agricultural socialized service level	0.0370 (0.14)	2.4798*** (4.32)
Urbanization rate	−0.4095 (−1.01)	2.0316*** (3.32)
Extent of trade openness to the outside world	0.3010** (2.46)	0.4895*** (3.52)
Proportion of primary industry	2.1743*** (6.66)	0.9502 (0.77)
Agricultural structure coefficient	0.8778*** (3.42)	2.8933*** (8.66)
Constant term	7.2932*** (25.90)	2.7776*** (6.48)
Sample size	130	170
Time	Regular	Regular
Area	Regular	Regular

*, **, *** stands for 10, 5 and 1% significant level, respectively.

agricultural practices resulting from urban development have contributed higher grain yields per unit area. In essence, the advancement of urbanization has had a beneficial impact on grain production. The correlation coefficient between the degree of trade openness to the outside world and grain yield is 0.6427, surpassing the 1% statistical significance level. This implies that increased openness to international trade led to the adoption of advanced agricultural production and management technologies, resulting in improved grain yields. Furthermore, a significant positive relationship exists between the share of the primary industry (agriculture) in the economy and grain yield. This study suggests that an increase in the agricultural share in the overall economy can positively improve grain yield. This improvement is likely attributable to the increased allocation of resources, investments, and attention to the agricultural sector, which in turn enhances grain production and subsequently yields. These findings underscore the importance of accounting for control variables in examining the correlation between agricultural factors and grain yield. Urbanization, trade openness, and the share of primary industry each exhibit significant positive associations with grain yield, highlighting the complex nature of agricultural production and the diverse factors that influence its success.

The coefficient of the agricultural structure significantly promotes grain yield, with an impact coefficient of 2.6091. This indicates that an increasing the proportion of land allocated crop planting can lead to a higher grain yield. To address the issue of endogeneity and eliminate any potential bias stemming from the causal relationship between the independent and the dependent variable, Model (3) was implemented. In this model, the lagged period of the development level of ASS was chosen as the instrumental variable to handle endogeneity. Additionally, Generalized Moment Estimation (GMM), renowned for its efficiency in addressing heteroscedasticity problems, was selected for the regression analysis. The results show that the level of ASS significantly contributes to an increase in gran yield at 1% significance level. This further strengthens the robustness and reliability of the regression results, indicating that the relationship between ASS and grain yield is dependable and unaffected by endogeneity issues. The results highlight the positive impact of the agricultural structure, specifically the proportion of crop planting area, on grain yield. The employment of instrumental variables and the application of GMM provide a solid approach to addressing potential endogeneity problems, reinforcing the credibility of the findings from the regression analysis.

Furthermore, to investigate the impact of ASS on grain yield in both main grain-producing and non-main grain-producing areas, this study categorized 30 provinces and cities across China accordingly. The impact of ASS on total grain yield in different regions was examined, and the regression results are presented in Table 7. Models (4) corresponds to the regression outcomes for main grain-producing regions, while Model (5) represent the regression results for non-main grain-producing regions. The study found that in main grain producing regions, the coefficient of the impact of ASS on grain production is 0.0370; however, this finding did not withstand the robustness test, signifying that the development of ASS in these regions does not have a significant effect on grain production.

Conversely, in non-main grain-producing regions, there is a significant correlation between ASS and grain production. The correlation coefficient is 2.4798, statistically significant at the 1% statistical level. This suggests that in non-main grain-producing areas, challenges such as farmers' part-time employment and non-main grain-production areas are more evident. These regions face greater constraints in terms of technology, land availability, labour force, and efficiency. Consequently, the demand for ASS among farmers is higher and more realistic. This study indicates that many hilly and mountainous regions are either lack access to ASS or face high prices, leading to the abandonment of arable land or suboptimal farming practices. Therefore, in non-main grain-producing regions, the level of ASS has a significant impact on grain production.

The development of ASS in non-main grain-producing regions is relatively advanced. The availability of service subsidy funds and the

TABLE 8 The results of the existence test of threshold effect.

Threshold variable	Model	F value	*p* value	10% critical value	5% critical value	1% critical value	BS frequency
Farmland transfer rate	Single threshold	33.65	0.0467	25.1807	34.7560	67.3120	300

TABLE 9 Results of the threshold value test.

Threshold variable	Threshold	Estimated value	Lower bound of 95% confidence interval	Upper bound of 95% confidence interval
Farmland transfer rate	Thresholdγ_1	0.3318	0.3269	0.3328

overall level of agricultural productivity contribute to the positive impact of ASS on grain yield in these regions. These services effectively support farmers in improving their agricultural practices, leading to an increase in grain production. Although ASS do not show a significant impact on grain yield in main grain producing regions, they play a crucial role in non-main grain-producing regions. The higher demand for these services, coupled with their advanced development, contributes to increased grain yield in these regions. The study underscores the necessity of taking into account regional variations and specific agricultural contexts when examining the relationship between ASS and grain production.

Tables 8, 9 presents the results of the threshold effect existence test and threshold value test, respectively. As mentioned earlier, this study introduces farmland transfer rate as a threshold variable to examine the non-linear relationship between the ASS development and grain yield increases. The study reveals that ASS exhibit a significant threshold effect on grain yield. The analysis indicates that there is a specific threshold value for the farmland transfer rate, which is determined to be 0.3318 based on the empirical findings. This threshold value signifies that once the rate of farmland transfer surpasses this threshold, the influence of ASS on promoting grain production becomes significantly stronger.

Moreover, the regression analysis results presented in Table 10 demonstrate that the impact of different agricultural land transfer rates on ASS and grain yield varies significantly. The results indicate that when the agricultural land transfer rate is below 33.18%, there is no significant correlation between ASS and grain yield. In other words, at lower levels of land transfer, the influence of ASS on grain production is not statistically significant. However, a significant shift is observed once the farmland transfer rate exceeds 33.18%. In such cases, the coefficient of influence between ASS and grain yield is calculated to be 1.1338, with both variables are statistically significant at the 1% significant level. This indicates a positive relationship between farmland transfer rate and the effectiveness of ASS in enhancing grain yield, aligning with the theoretical predictions (Chen T. et al., 2022; Yang and Li, 2022). The transfer of farmland can facilitate and enhance the positive effects of ASS on increasing grain yield. It implies that promoting farmland transfer, particularly when it surpasses the identified threshold, can be beneficial for optimizing the impact of ASS on grain production.

Discussion

Food security has consistently been a significant concern for China, a populous developing nation with a population exceeding 1.4 billion. The concept of food security in China has consistently prioritized ensuring a sufficient grain supply. This emphasis on grain sufficiency has been a fundamental aspect of China's national agenda for food security (Bishwajit et al., 2013) for several decades. For instance, China's economic reform commenced by undertaking a substantial overhaul of the agricultural sector, placing immense emphasis on the cultivation of cereal grains (Nolan, 1983). The process of de-collectivization, initiated in the late 1970s, was instrumental in bolstering both farm output and efficiency, leading to remarkable advancements (Nolan, 1983; Unger, 1985). Regional grain self-sufficiency has been a predominant catalyst behind these notable achievements (Yifulin and Jameswen, 1995). China's achievement of grain self-sufficiency is due to two primary approaches (Niu et al., 2022). The first is the successful implementation of agricultural restructuring, rural infrastructure improvement, technological advancement, price support with subsidies, and land management policies. The second strategy involves China positioning itself as a net importer of grain, leveraging policies that encourage market openness to maintain its self-sufficiency.

Grain security is a fundamental aspect of food security, given that grains like rice, wheat, and maize constitute staple foods for a significant portion of the global population (Albahri et al., 2023; Hu et al., 2023). Meanwhile, China's grain security encounters several persistent challenges. These include the loss of arable land to degradation and urbanization, water resources scarcity, natural disasters, the effects of climate change, growing demand due to population growth and rising living standards, a small-scale agricultural economy dominated by smallholder farmers, and outdated agricultural infrastructure, among various other factors (Wang et al., 2009). Additionally, the development of urban-based industries has attracted huge rural labour migration to cities. To address these challenges, there has been a shift towards part-time management in agricultural production. Many farmers have opted to utilize services like agricultural mechanization to minimize the opportunity costs associated with dividing their time between farming in rural areas and seeking employment in urban areas (Zang et al., 2022; Wang and Huan, 2023).

During the first decade of reform and opening up (1983–1990), there was significant progress in the establishment of ASS entities (Huang et al., 2020). This period primarily focused on the initial development of these services, with a particular emphasis on public welfare-driven initiatives. Gradually, the industry structure for ASS established. The emergence of producer service industry, centred on production trusteeship, has played a pivotal role in driving China's agricultural development to a new phase, laying the groundwork for the strategic positioning of ASS as a key industry. As of the end of

TABLE 10 The results of the threshold effect regression.

Variables	Threshold variable: rural land transfer rate
	Model (6)
	Grain yield
ASS level (farmland transfer rate < γ 1)	0.6119 (1.23)
ASS level (farmland transfer rate > γ 1)	1.1338** (4.57)
Urbanization rate	1.8034*** (0.73)
Extent of trade openness to the outside world	0.0986 (0.80)
Proportion of primary industry	3.1239*** (3.60)
Agricultural structure coefficient	1.7553*** (4.79)
Constant term	0.1587*** (10.59)
Sample size	300

*, **, *** stands for 10, 5 and 1% significant level, respectively.

2020, approximately 900,000 providers of ASSs in China had served an extensive area of farmland exceeding 107 million hectares. Of this, 60 million hectares were allocated for grain cultivation (Huan and Zhan, 2022; Wang and Huan, 2023).

The effect of ASSs on grain yield

This study conducted a detailed investigation of the agricultural services provided by social organizations, exploring how these services affect the grain production output. The study established an index evaluation system and identified five ASS types of ASS to evaluate their comprehensive effect on grain production output (Table 2). According to the empirical results, ASS has a significantly positive impact on grain yield, indicating that an increase in the level of ASS can lead to a higher grain yield level. This finding is consistent with the recent studies that have investigate the effect of ASS (Cheng et al., 2022; Huan et al., 2022). Surprisingly, the role of ASS in enhancing grain yield remains persistent even after controlling for other factors that could potentially influence grain yield. In essence, the study's results demonstrate that the positive impact of ASS on grain yield cannot be readily attributed to other influencing factors, emphasizing the importance of these services in improving agricultural productivity (Chen T. et al., 2022).

Furthermore, Lu and Huan (2022) conducted research on the impact of agricultural labour transfer on grain production in China. They found that this transfer positively affects grain production both directly and indirectly, facilitated through increased use of agricultural machinery. This study corroborates these findings, indicating that smallholder farmers primarily receive agricultural machinery via ASS entities. These services help to reduce input costs and ease the adoption of agricultural machinery, thereby making it more accessible to smallholder farmers. This underscores the significance of ASS in promoting the use of agricultural machinery and boosting grain production in China.

The regional disparity of ASS effect on grain yield

This study finds that the influence of ASS on grain yield varies significantly between main grain-producing regions and non-main grain-producing regions. Interestingly, it reveals that the positive effect of ASSs on increasing grain yield is more pronounced in non-main grain-producing regions than in main grain-producing regions. This result implies that the implementation and impact of ASS could boost grain yield in regions where agriculture is not the primary focus. This may be attributed to the relatively lower levels of existing agricultural support and infrastructure in these regions. These results underscore the importance of considering regional agricultural dynamics and resource allocation when designing and implementing agricultural development strategies. This is particularly pertinent for non-main grain-producing regions where the potential impact of ASS on grain yield appears to be more substantial.

According to Wang and Huan (2023) argument, grain production efficiency in China exhibits an unbalanced spatial development, characterized by a decreasing trend from the central area towards the eastern and western regions. This variation in efficiency may stem from the capacity differences of smallholder farmers to access agricultural inputs and the level of developmental state of ASS organizations that provide these inputs. The study suggests that the uneven distribution of grain production efficiency among regions may stem from the varied availability and accessibility of agricultural inputs. This variation can depend on the capacity of smallholder farmers to obtain these inputs and the extent to which ASS organizations in providing support services. These findings highlight the necessity of focused interventions aimed at improving agricultural infrastructure and support services in underdeveloped regions, thereby promoting more balanced and sustainable development of grain-producing regions in China.

The threshold effect of farmland use right transfer on the effect of ASS on grain yield

According the results of the threshold model analysis, the impact of ASS on grain yield increase is not linear (Table 10). A critical point exists where farmland use right transfer triggers a notable effect on grain yield. Once the rate of farmland transfer exceeds this threshold, the contribution of ASS to enhancing grain production becomes more evident. These findings suggest that the impact of ASS on grain yield varies with different levels of farmland transfer, and there is a critical point where the transfer of farmland has a notable effect on this relationship. These insights can inform policy interventions designed to promoting sustainable agricultural development and improving the efficiency of ASS in China.

The threshold effect observed in the relationship between farmland use transfer and the effect of ASS on grain yield can be explained to several factors. For instance, when the rate of farmland uses transfer falls below the identified threshold, it implies that there might not be significant changes in farmland ownership or management. Under these circumstances, the impact of ASS on grain yield could be limited since the existing farmers may already possess the necessary resources and support. Consequently, the correlation between ASS and grain yield is not statistically significant. Conversely, when the rate of farmland use transfer surpasses a certain threshold, it indicates a higher level of land circulation and potentially more significant changes in the agricultural production system. The transfer of farmland can result in the consolidation or aggregation of farmland, enabling economies of scale and improved resource allocation. This, in turn, creates opportunities for ASS to exert notable significant effect on grain yield. Additionally, when there is a higher rate of farmland use transfer, it implies increased participation of different stakeholders, such as agricultural cooperatives or large-scale farming enterprises. These entities typically have improved access to resources, technologies, and knowledge, which can be enhanced through ASS. Consequently, the synergistic impact of farmland use transfer and ASS becomes more significant in boosting grain yield.

Furthermore, farmland transfer serves as an effective method for reducing transaction costs associated with ASS, while also enabling farmers to consolidate small-scale and dispersed farmland. For instance, conventional agricultural machinery services face challenges when operating on fragmented farmland, which can be fuel consuming and inaccessible. Additionally, farmers are approaching service providers individually to negotiate fees. As a result, agricultural machinery services become reluctant to operate in villages with a lower degree of farmland transfer, preferring instead to collaborate with large-scale farmers who can offer more competitive unit prices. Thus, regions with a higher degree of farmland transfer tend to attract more agricultural machinery services t compared to regions with fewer farmland transfers.

Conclusion and policy implication

Given the rapid population growth, urbanization, and climate change, it is crucial to support smallholder farmers by empowering them, reducing inequalities, and ensuring inclusive participation in the pursuit of global food security and sustainable development. In order to overcome these challenges, smallholder farmers require specialized training through knowledge transfer and training programs, adoption of appropriate agricultural technologies, market access, and resource availability. Although extensive research has examined the effects of ASS on smallholder farmers' agricultural production, suggesting that these services encourage the adoption of environmentally friendly agricultural practices (Cai et al., 2022; Chen Z. et al., 2022; Cheng et al., 2022; Ren, 2023). It also increases the demand for large- and medium-sized agricultural machinery, and promote labour transfer among grain producers (Chen T. et al., 2022), as well as mitigate the negative effects of rural labour migration (Wang and Huan, 2023). Little focus has been paid on the direct effect of these services on smallholder farmers' grain production in China. This study analyses the impact of the development level of ASS on China's food production. An evaluation index system for ASS was developed to assess its influence on grain yield improvement, utilizing provincial panel data from 2011 to 2020. The study also examined how this effect varies between the main grain-producing regions and non-main grain-producing regions. Additionally, the study investigated the role of farmland use right transfer as a threshold variable that influences the relationship between ASS and grain yield.

The main findings of this study are threefold: (1) the development of ASS has a significantly positive impact on increasing food production, evidenced by a correlation coefficient of 1.3555 at the 1% significance level. (2) In the main grain-producing regions, the influence of ASS on food production is not significant. In contrast, in areas that do not primarily produce grain, ASS contribute to an increase in food production. (3) When considering the level of farmland use right transfer as a threshold variable, a distinct threshold value emerges at 33.18%. Farmland use right transfer enhances the impact of ASS on increasing food production.

Incidentally, this study outlined several policy implications from three distinct perspectives:

Policy implications arising from the regional variation of ASS effect on grain yield improvement

This empirical study evidenced that the development of ASS has a positive and significant effect on the improvement of grain yield. Other scholars have provided a similar assertions (Huan et al., 2022; Yang and Li, 2022; Wang and Huan, 2023). This implies that policymakers should prioritize the development of ASS to promote sustainable agricultural growth in China. A potential policy intervention could involve increase public investment in ASS infrastructure, including irrigation systems, agricultural machinery, and storage facilities. Improving the accessibility of these services for farmers, particularly those who are small-scale and may lack access to necessary resources independently, is possible. Additionally, policies that encourage private sector investment in ASS can enhance both the availability and quality of these services, ultimately contributing to increased grain yield.

An essential policy implication lies in the imperative need to tackle barriers impeding the widespread adoption of Agricultural Support Services (ASS). Awareness gaps among farmers and financial constraints often hinder the effective utilization of these services. Addressing these challenges requires decisive policy interventions, including targeted educational initiatives, comprehensive training programs, and strategic subsidies to facilitate ASS utilization. Such measures are crucial in dismantling barriers and catalyzing the widespread adoption of these services. This underscores the critical role of investing in ASS as a cornerstone for driving sustainable agricultural progress in China. To drive agricultural productivity, alleviate poverty, and bolster food security, policymakers must prioritize the advancement and advocacy of these vital services with unwavering commitment.

Policy implications derived from the regional characteristics of ASS effect on grain yield improvement

The implications drawn from this study, which highlighted the varying effects of ASS on grain yield between main grain-producing and non-main grain-producing regions, hold significant implications for policy-making. The findings emphasize the necessity for targeted development approaches based on regional characteristics. Main grain-producing regions should focus on integrating ASS with current farming practices to maximize grain yield. In contrast, non-main grain-producing regions require increased investment and prioritization to boost their agricultural productivity. Moreover, understanding the varying effects of ASS on grain yield can guide decisions regarding resource allocation.

Non-main grain-producing regions show a greater potential for increased grain yield through the implementation of ASS, highlighting the importance of appropriate resource allocation to bolster their agricultural development. By recognizing the varying effects of ASS in different regions, policymakers can strive toward promoting equitable agricultural development. Strategies ought to focus on narrowing the gap between main and non-main grain-producing regions, ensuring that every region has access to essential resources and support to enhance their grain yield production. The insights gained from these implications are crucial for policymakers in designing effective strategies to foster sustainable agricultural growth and achieve equitable grain production across different regions.

Policy implication arising from the threshold effect of farmland use right transfers on the effect of ASS on grain yield

The findings that the impact of ASS on grain yield growth is not linear, and that there exists a critical threshold at which farmland use right transfer triggers a notable effect on grain yield, carries significant policy implications. Policymakers should consider developing tailored interventions that reflect the level of farmland transfer. For example, policies that encourages ASS adoption in regions where the rate of farmland transfer exceeds this threshold could significantly enhance grain production. Policymakers should prioritize investments in improving the efficiency of ASS to maximize their impact on grain production. This may involve focusing on specific types of services proven to significantly boost grain productivity, especially in regions where farmland transfer has surpassed a critical threshold. Similarly, policymakers should work to facilitate farmland transfer in a sustainable and equitable manner, considering the needs of different stakeholders, including small-scale farmers and rural communities. In doing so, policymakers can foster sustainable agricultural development and enhance the overall efficiency of ASS in China.

This research paper holds empirical, theoretical, and practical significance. Its empirical contributions shed light on the relationship between ASS, farmland transfer, and grain yield, revealing the diverse impacts across different regions. The theoretical contributions deepen our understanding of the complex dynamics involved in promoting food security through ASS. Its practical implications provide guidance to policymakers and stakeholders in developing strategies that strengthen the impact of ASS on agricultural productivity and food security. In conclusion, this study highlights the essential role of ASS in enhancing grain yield in China. It provides valuable insights for policymakers and stakeholders working to enhance agricultural productivity and improving the lives of Chinese farmers.

While this study has its merits, it is not without limitations. This study does not consider the indirect effects that ASS have on grain yield, such as those achieved by strengthening of rural community resilience. Through promoting cooperation, resource sharing, and collective action, ASS can contribute to building stronger, more resilient agricultural communities, which could in turn positively affect grain yields. These limitations underscore the importance of further research and comprehensive data collection to fully understand the complex dynamics between ASS, grain yield and land tenure changes.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: data on grain yield, agricultural socialized services, agricultural structure coefficient, and farmland use transfer were obtained from China's Rural Statistics Yearbook (CRSY) https://www.stats.gov.cn/zs/tjwh/tjkw/tjzl/202302/t20230215_1907997.html. Data on urbanization rate and openness to the outside world were derived from the National Bureau of Statistics (NBS) https://data.stats.gov.cn/, while data on the primary industry were extracted from China's National Statistics Yearbook (CNSY) https://www.stats.gov.cn/sj/ndsj/2022/indexeh.htm.

Author contributions

BC: Writing – review & editing, Conceptualization, Data curation, Funding acquisition, Methodology, Resources, Software, Supervision, Visualization, Writing – original draft. LW: Writing – review & editing, Methodology, Formal analysis. FS: Visualization, Writing – review & editing, Conceptualization, Methodology, Project administration, Resources. MA: Conceptualization, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing, Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation. BG: Conceptualization, Methodology, Visualization, Writing – review & editing, Software, Writing – original draft. AA: Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing.

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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.

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EDITED BY
Josef Abrham,
Czech University of Life Sciences Prague, Czechia

REVIEWED BY
Yan Liu,
Huanghuai University, China
Choon Sen Seah,
Tunku Abdul Rahman University, Malaysia

*CORRESPONDENCE
Duanyang Zhao
✉ juexuezdy@126.com

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

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The influence of online information on consumers' channel migration behavior of fresh agricultural products

Ningbo Cui†, Jin Dong†, Xiaofan Fan, Duanyang Zhao*, Mingshuo Liang and Jiaoyu Shi

College of Economics and Management, Northeast Agricultural University, Harbin, China

Introduction: Compliance with the latest patterns in online consumption of fresh agricultural products should prioritize the shifts in consumer behavior. This study aimed to clarify the influencing factors of consumers' channel migration behavior of fresh agricultural products. While the migration of consumers' consumption of fresh agricultural products to online channels is an undeniable fact, and this trend continues, literature on this topic remains limited.

Methods: Based on SOR theory, and from the dual perspectives of information transmission and information reception, this study exploratively introduced the network affinity of consumers, and constructed the concept model of the influencing factors of consumers' channel migration behavior of fresh agricultural products including information acquisition and risk perception. 416 valid questionnaires were used to conduct structural equation model analysis.

Results: The results confirm that product information and platform information significantly affect consumers' channel migration behavior of fresh agricultural products. Product information including feature information and price information has a positive influence on consumers' channel migration behavior of fresh agricultural products. The same is true for such behavior and the platform information including service information and logistics information. Risk perception plays a partial mediating role in the influence of product information variables and platform information variables on consumers' online purchasing and migration behavior of fresh agricultural products. Network affinity negatively moderates the causal relationship between product information and risk perception as well as that between platform information and risk perception. The effect is more pronounced for consumers with high network affinity than those with low network affinity.

Discussion: The study presented in this paper offers a replicable theoretical framework for future discussions on consumer channel migration behavior, and enriches the literature on consumer online consumption behavior. It is highly meaningful for further improving the online consumption stickiness, tapping the potential of online consumption and improving the circulation efficiency of fresh agricultural products in the post-pandemic era.

KEYWORDS

fresh agricultural products, channel migration behavior, online information, risk perception, network affinity

1 Introduction

With the rapid development of platform economics and the continuous progress of cold chain logistics technology, China's fresh agricultural industry is growing quickly. In light of this, buying fresh agricultural products online has become a new direction of consumption development, and the domestic online sales scale of fresh agricultural products is gradually expanding (Yan et al., 2020). According to statistics, the transaction scale of domestic fresh e-commerce exceeded 80 billion dollars in 2022, with a year-on-year growth of 20.25%. Online purchase of fresh agricultural products can break time and space constraints, expand product coverage, enhance selectivity, and meet diversified needs. It can also effectively improve the efficiency of communication between buyers and sellers, bringing less turnover links and lower circulation costs. These advantages of online consumption are increasingly recognized by more and more consumers (Guo J. et al., 2022; Wang and Jia, 2023). Especially during the COVID-19 epidemic, online purchase of fresh agricultural products has brought more convenience to consumers. Contactless distribution has reduced the time cost and infection risk, encouraging a shift in fresh agricultural product consumption to online channels (Xie et al., 2022; Jiang et al., 2023). Although the traditional offline retail channel is still the main sales method of fresh agricultural products in China, a trend of consumers' online channel participation and an increase of online user penetration rate are emerging due to the epidemic (Pu et al., 2022). While online consumption is becoming more mainstream, e-commerce platforms need to adapt to consumers' preferences to ensure a more sustainable development in the evolving business environment and growing market competition (Zhang et al., 2020; Shariffuddin et al., 2023). Purchase channel migration of consumers is an important indicator reflecting the development of fresh agricultural products market, in the post-epidemic era, fresh e-commerce enterprises can formulate marketing strategies to attract more consumers by clarifying the key factors affecting consumers' channel migration behavior of agricultural fresh products. This will help to shape consumers' online fresh consumption habits, which in turn will increase the stickiness of fresh agricultural products' online consumption and expand the online consumption space.

Existing research has extensively explored the factors influencing consumers' online purchasing migration behavior for fresh agricultural products, with risk perception being an important determinant (Liu and Wu, 2020; Wang et al., 2022). Consumers usually face some unavoidable exogenous risks when choosing purchase channels. Consumers' willingness, possibility and frequency to buy fresh agricultural products online will decrease as a result of their perception of risk (Hsieh and Tsao, 2014; Lazaroiu et al., 2020). As for the cause of risk perception, the classical economic explanation is the adverse selection and moral hazard caused by information asymmetry. Although online ordering is convenient and fast, it is difficult for online channels to provide consumers with an intuitive experience and personalized services. Since consumers cannot check the physical objects on site before placing orders, they cannot effectively identify online fresh agricultural products' quality and value (Lee et al., 2019; Yang et al., 2021). Meanwhile, consumers are very sensitive to the safety of fresh agricultural products, but purchasing fresh agricultural products online has the inherent disadvantages of long return and replacement cycles with incidental costs. Once the product quality problems or product quality is not up to expectations, return and replacement will directly lead to conflicts of interests between the two parties in the transaction and further strengthen consumers' risk perception (Mahapatra and Mishra, 2021). In addition, to pursue short-term sales and profits, online platform sellers may publish false information or even carry out speculation. Some consumers may not choose online channels for risk aversion (Tao et al., 2021). Therefore, to promote the healthy development of the online consumption market of fresh agricultural products, efforts should be made to reduce the risk perception of online purchase migration by improving information symmetry.

Information acquisition is the process of consumers' information collection, identification and acceptance. Effective information acquisition plays a positive role in reducing consumer risk perception. The reduction of risk perception is actually to cause cognitive change or persuasion of consumers, and the information display and transmission in this process is essential (Tung et al., 2012). The current speed of consumer information dissemination is rapidly increasing under the catalysis of the network. In this regard, the academic community has further discussed the transmission effect of different information content. These studies focus on exploring feasible ways to reduce consumers' risk perception from the perspective of information transmission, and affirm the value of product information and platform information in reducing information asymmetry and consumer risk perception of fresh agricultural products (Cang and Wang, 2021; Lin et al., 2021). However, information transmission is a process involving both supply and demand in the market. Effective information acquisition requires not only online sellers to make efforts in information disclosure and transmission, but also consumers to take the initiative to search for information. Currently, China is in a period of rapid development of the Internet. Various new media platforms provide a feasible way for consumers to acquire useful online information about fresh agricultural products, and online information has become the driver of consumers' online consumption. Only when consumers obtain more useful information online can they comprehensively know online fresh agricultural products and make choices on the shift to online purchases (Jun and Park, 2016), which is consistent with the laws of information dissemination. In other words, online information demands are the foundation of the channel migration behavior from offline to online. Consumers tend to acquire relevant online information before making online purchasing migration behavior of fresh agricultural products. Many scholars have discussed the role of information search in consumers' purchasing behavior regarding genetically modified food, dairy products, durable goods, and electronic products (Dutta and Das, 2017; Zhu et al., 2018; Li et al., 2021; Yang et al., 2022). Additionally, some scholars have emphasized the beneficial value of online information display from the perspective of information transmission in previous research on consumers' channel migration behavior of fresh agricultural products of fresh agricultural products (Guo H. et al., 2022; Zhao, 2022; Li et al., 2023). Regrettably, the majority of these studies still lack sufficient attention to consumer information acquisition, so more pertinent studies are needed.

Therefore, we attempt to answer the following questions:

> RQ 1: Does risk perception have a negative impact on consumers' channel migration behaviors when it comes to fresh agricultural products?

> RQ 2: How does different online information affect consumers' risk perception?
>
> RQ 3: How does consumer information acquisition affect the impact of online information on risk perception?

To address these issues, based on SOR theory, and from the dual perspectives of information transmission and information reception, this study exploratively introduced the network affinity of consumers, and constructed the concept model of the influencing factors of consumers' channel migration behavior of fresh agricultural products including information acquisition and risk perception. The field survey data of 416 fresh agricultural products consumers in Harbin, Heilongjiang Province, was used for this study. The effects of product information, platform information and risk perception on consumers' channel migration behavior of fresh agricultural products, as well as the moderating effect of network affinity, were empirically tested. The following three factors primarily represent the scientific contributions of this study as compared to earlier investigations. First, based on the SOR model, it constructs a conceptual model of online purchasing migration behavior of fresh agricultural products including information acquisition and risk perception, which provides a replicable analytical framework for future discussions on consumer channel migration behavior, and helpful to expand the theoretical research on consumer purchasing channel migration. Secondly, from the perspective of information dissemination, this study exploratively introduced the network affinity of consumers, the online information of fresh agricultural products and the network affinity of consumers are included in the same analysis framework, which not only reflects the openness of online market information of fresh agricultural products from the perspective of information transmission, but also pays attention to consumers' information acquisition ability from the perspective of information reception. Thirdly, based on the differences in consumers' ability to access information, the consumer data with high network affinity and low network affinity are analyzed by quantitative method, respectively. The various responses of information access to risk perception of the two specific groups were then analyzed collectively. The research of this paper not only provides new empirical evidence for accelerating the improvement of online channels for fresh agricultural products, but also provides new ideas for accelerating consumers' migration to online purchase of fresh agricultural products, and provides practical inspiration for the online marketing of the e-commerce of fresh agricultural products, which will contribute to the sustainable development for e-commerce of fresh agricultural products.

The remaining part of this paper is organized as follows. Section 2 constructs a conceptual model, theoretically analyzes the influencing factors of consumers' channel migration behavior of fresh agricultural products of fresh agricultural products and puts forward research hypotheses. Section 3 introduces the research methods, variable selection, data sources and sample characteristics. Section 4 provides the results of the study. Section 5 is a discussion. Section 6 presents conclusions, policy recommendations and future perspectives.

2 Theoretical analysis and research hypothesis

2.1 Conceptual model

In 1974, Mehrabian and Russell put forward the SOR model based on environmental psychology, which originated from the SOR model (Stimulus-Organism-Response Model) first proposed by Woodworth in 1926 on the basis of the Stimuli–Response Theory (Lin et al., 2021; Xu et al., 2022). The SOR model recognizes human intrinsic factors and adds the middle between stimulus and response as a mediator variable (Xu et al., 2022). The model deconstructs the whole process from the stimulus to the behavior and provides theoretical support for the in-depth analysis of the intrinsic state change after the stimulus. It is widely used in psychology, behavioral economics and management research (Yuan et al., 2020; Brinda et al., 2022). In the field of consumer behavior research, it is commonly used to explain how environmental stimuli affect consumer psychological changes and then act on consumer market participation behavior (Yuan et al., 2020). The process of consumers' purchasing decisions moving from one channel to another is called channel migration. In recent years, information search and online orders have been completed anytime and anywhere through smart phones, which occupies more and more fragmented time of consumers and promotes cross-channel purchasing behavior. Online information is an important factor influencing consumer behavior. From the perspective of information dissemination laws, effective information transmission relies on both the information source and the information itself, as well as the ability of the information recipient to access and correctly understand the information. In the digital age, the consumption scenario of fresh agricultural products has shifted from offline to online, with consumer decisions transitioning from being determined by the products themselves to being influenced by the online product information. Consumers engage in online information acquisition, comparison, and interaction, and to some extent, the precision of information embedded in the consumption scenario directly determines consumer behavior. This article employs the SOR model as a theoretical framework, which is commonly used in existing research to analyze consumer online purchasing behavior. For instance, Tian et al. (2022) focused on the impact mechanism of mobile short video advertising on the consumption behavior of young people based on the SOR model (Tian et al., 2022). Wu and Huang (2023), based on the SOR model, explored the impact of perceived value and trust on consumers' continuous purchase intention in live-streaming e-commerce (Wu and Huang, 2023). Therefore, previous studies support the applicability of the SOR model in explaining the effects of external environmental stimuli on individual consumers and their behavioral responses. Based on the above analysis, this paper constructs a conceptual model of influencing factors of consumers' channel migration behavior of fresh agricultural products of fresh agricultural products (see Figure 1), in which information acquisition as a stimulus variable will affect consumers' risk perception of online purchase of fresh agricultural products, and thus affect consumers' channel migration behavior of fresh agricultural products of fresh agricultural products. It is discussed specifically as follows. (1) Existing studies usually focus on product information, including feature information and prices information, and platform information, including service information and logistics information as stimuli (Wu and Zhu, 2015; Ren and Le, 2018). Few studies concentrate on consumer factors. In this paper, consumers' online information acquisition ability is measured by network affinity, so the "Stimulus" variable integrates product information, platform information and network affinity. (2) "Organism" refers to consumers' risk perception, reflecting consumers' subjective judgment on the risk of online purchase of fresh agricultural products. (3) "Reaction" refers to consumers' online purchasing migration behavior of fresh agricultural products.

2.2 Theoretical analysis and research hypothesis

2.2.1 Product information, platform information, and channel migration behavior

Product features are important indicators to measure the value of fresh agricultural products. The freshness of the quality, the standardization degree of outer packing and the complete degree of certification are basic for consumers to judge the quality of fresh agricultural products in advance (Watanabe et al., 2021; Wang and Jia, 2023). The more abundant product feature information provided by online channels, the easier it is for consumers to be attracted to online channels for consumption. On the one hand, online channels have transcended the temporal and spatial constraints of traditional offline consumption, so consumers from different regions purchase fresh agricultural products with same price. The transparent and fair pricing information provided by online channels will prioritize consumers to choose online purchasing channels. On the other hand, due to the sensitivity to product price, consumers will give priority to transaction costs when choosing purchase channels, so they tend to choose low-price and better-deal products (Chen and Wang, 2018). Based on the discussion above, this paper proposes the following hypothesis:

> H1a: Feature information (FEI) positively affects channel migration behavior (CMB).
>
> H1b: Price information (PRI) negatively affects channel migration behavior.

Online channels provide opportunities for information disclosure and exchange among consumers, and merchants with reliable sources and high reputation levels promote consumers' online purchases (Ma, 2019). Online service is an important path to close the distance between businesses and consumers. Good service quality will encourage consumers to choose to buy fresh agricultural products online. In addition, due to the perishability and timeliness of fresh agricultural products, consumers pay more attention to the logistics delivery time and whether it is delivered safely. High-quality logistics can enhance consumers' expectations of online purchases of fresh agricultural products (Wang and Zhang, 2020). Based on the above discussion, this paper proposes the following hypothesis:

> H1c: Service information (SEI) positively affects channel migration behavior.
>
> H1d: Logistics information (LOI) positively affects channel migration behavior.

2.2.2 Product information, platform information, and risk perception

Online channels can provide complete and rich information on product features, including not only basic features such as product type, packaging and origin, but also food certification characteristics such as production standardization and quality and safety. These can enhance consumers' certainty about the quality and safety of fresh agricultural products and improve consumers' trust and reduce their perception of risk (Yue et al., 2017). Fresh agricultural products are mostly necessities. Although the price elasticity of demand is generally small, consumers tend to be more price-sensitive. The fairness of product prices is a major concern for consumers. Compared with traditional offline channels, online channels have the price advantage of economies of scale. Meanwhile, online platforms provide convenience for consumers to search for information and compare prices (Bodur et al., 2015; Bhatnagar et al., 2021). In other words, consumers tend to buy fresh agricultural products similar to those available offline at more favorable prices. Price discounts and promotions online release more dividends, which increase consumers' sense of value acquisition and help consumers reduce the perception of risk. According to the discussion above, this paper puts forward the following hypothesis:

> H2a: Feature information (FEI) negatively affects the risk perception (RP).
>
> H2b: Price information (PRI) positively affects the risk perception.

Online platforms not only provide consumers with real-time customer service and interaction, but also display comprehensive reviews of products. Consumers can gain a comprehensive understanding of products through interaction with merchants and evaluations from other consumers. Therefore, the high-quality services provided by merchants can increase consumers' emotional experience and effectively reduce their loss (Li and Zhang, 2018). Meanwhile, good website design is more convenient and reliable for consumers. There are many uncertainties in the process of transport and delivery of online products before receipt. The occurrence of these problems will increase consumers' perception of risk (Jin, 2021). According to the discussion above, this paper puts forward the following hypothesis:

> H2c: Service information (SEI) negatively affects the risk perception.
>
> H2d: Logistics information (LOI) negatively affects the risk perception.

2.2.3 Perception and channel migration behavior

Compared with offline channels, online purchasing of fresh agricultural products leads to more uncertainty, so consumers' risk perception coefficient is higher (Zia et al., 2022). According to the loss-aversion theory, potential risks are harder for customers to take than possible advantages, and logical customers would actively consider the likelihood that a risk will materialize as well as the potential losses before deciding to make a change (Teng and Ming, 2023). Consumers

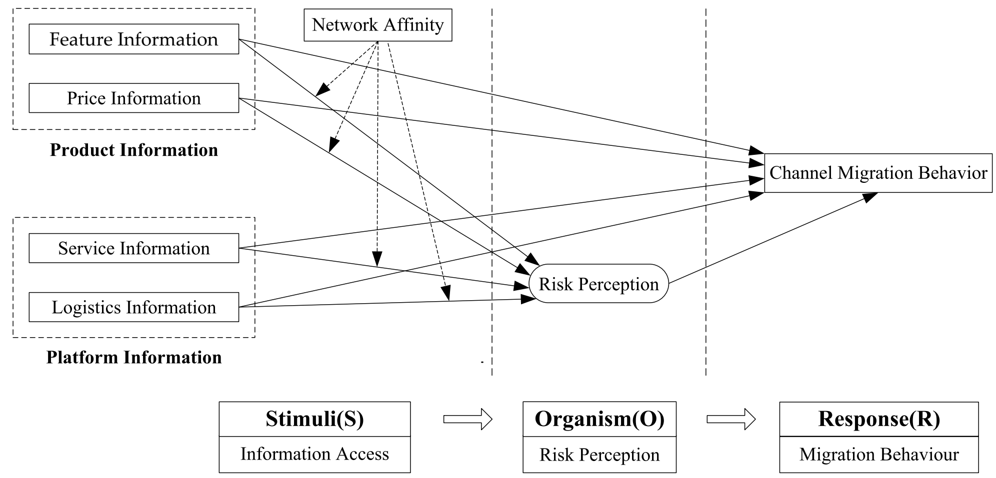

FIGURE 1
Conceptual model.

may perceive multiple risks when deciding whether to switch to buying fresh produce online. Therefore, the chance that consumers migrate to online channels decreases as their perceived risk of online products increases, when purchasing online, consumers are more inclined to choose reputable merchants with higher product and service quality and lower potential risks (Wang et al., 2021). Risk perception is an important restriction factor affecting consumers' online purchasing migration behavior of fresh agricultural products. Based on the discussion above, this study proposes the following hypothesis:

> H3: Risk perception negatively affects channel migration behavior of fresh agricultural products.

2.2.4 Mediating effect of risk perception

In the online market environment, the display of abundant online information can reduce the possibility that the consumer cannot truly perceive the problem of the fresh agricultural products and reduce the risk that the consumer does not understand the purchased product. Efficient and complete interactive experience of product information and platform information strengthens the psychological connection between online products and consumers to a certain extent. It also plays a role in promoting consumers' sensory recognition (Chen and Li, 2023). It satisfies the needs of consumers and enhances the identity of online purchases. Therefore, the presentation of online information dissolves informational barriers. Specifically, it reduces information asymmetry and realizes the rapid and effective transmission of information, which lessens the perception of risk among consumers while providing them with a varied online shopping experience. It thereby lowers the psychological barriers to online consumption for consumers and encourages the online channel migration of fresh agricultural products (Cheng et al., 2019; Wang and Bu, 2021).

> H4a: Risk perception has a mediating effect on the influence of feature information on channel migration behavior of fresh agricultural products.

> H4b: Risk perception has a mediating effect on the influence of price information on channel migration behavior of fresh agricultural products.

> H4c: Risk perception has a mediating effect on the influence of service information on channel migration behavior of fresh agricultural products.

> H4d: Risk perception has a mediating effect on the influence of logistics information on channel migration behavior of fresh agricultural products.

2.2.5 Moderating effect of network affinity

The Internet is accelerating the present rate at which information is disseminated. Consumers, in order to ensure a better online shopping experience for fresh products, create a desire for knowledge by acquiring more pertinent online information. Network affinity represents consumers' preference for the Internet and cumulative degree of experience in network behavior. Consumers with more Internet experience will be more adept in the process of Internet browsing, easier to quickly search for information they are interested in and have a higher perception of online products than consumers with lower network affinity (Wang et al., 2016). Higher network affinity helps to reduce consumers' risk perceptions. On the one hand, consumers proficient in online searches have a higher level of acceptance when faced with new things and are more likely to proactively acquire the information they need during the online purchasing process, and enhance their perceived ability of online purchases. On the other hand, the more experienced consumers are with the Internet, the more likely they are to find the advantages of buying fresh agricultural products online. Thus, their perception of risk can be reduced (Han and Kang, 2022). Based on the above discussion, this paper proposes the following hypothesis:

H5a: Network affinity (NA) plays a moderating role in the influence of feature information on risk perception.

H5b: Network affinity plays a moderating role in the influence of price information on risk perception.

H5c: Network affinity plays a moderating role in the influence of service information on risk perception.

H5d: Network affinity plays a moderating role in the influence of logistics information on risk perception.

3 Research design

3.1 Model construction of structural equation model

Structural equation modeling is suitable for analyzing the relationship between multiple types of variables, with the advantage that multiple indicators and variables can be handled together, avoiding the errors in evaluation results brought about by the traditional method of studying one indicator alone. It is divided into two categories: covariance-based structural equation modeling (CB-SEM) and variance-based partial least squares structural equation modeling (PLS-SEM). The variables set in this paper, such as product information, platform information, and risk perception, are all indirectly measured latent variables. Thus, PLS-SEM is chosen to conduct empirical analyses considering the research purpose of this paper. The PLS-SEM analysis is divided into two parts: the measurement model and the structural model. The measurement model, also known as the validated factor analysis model, is used to observe the relationship between variables and latent variables. The measurement model is generally composed of two equations with the following expressions, respectively:

$$X = \Lambda x \xi + \delta$$

$$Y = \Lambda y \eta + \varepsilon$$

x is the exogenous observed variable, ξ is the exogenous latent variable, Λx is the factor load of indicator x at ξ, and δ is the measurement error. y is the endogenous observed variable, η is the endogenous latent variable, Λy is the factor load of index y on η, ε is the measurement error. Latent variables and measurement error are independent of each other Structural models, also known as latent variable causality models, represent relationships between latent variables. The specific expression for the structural model is:

$$\eta = B\eta + \Gamma\xi + \zeta$$

B is the path coefficient, representing the relationship between endogenous latent variables; Γ is the path coefficient, representing the influence of exogenous latent variables on endogenous latent variables; ζ is the measurement error.

3.2 Variable selection

The explanatory variables of this study are the latent variable consumers' channel migration behavior of fresh agricultural products of fresh agricultural products, which are mainly determined by three observable variables: interest in purchasing fresh agricultural products through online channels, the possibility of channel migration of fresh agricultural products, and online channel recommendation. The variables above are measured using a 5-point Likert scale ranging from "very low" to "very high," with 1 to 5, and 3 being the neutral option. The product information and platform information are among the external environmental data that the study examined. The product information has two variables: feature information and price information. The feature information has three measurement items: the degree of certification, the degree of packaging standardization, and the quality of the fresh agricultural products online. The price information has two measurement items: the strength of the price concessions and the fairness of the price. Platform information consists of service information and logistics information. Three measurement items are used to measure the former: the degree of professionalism in customer service, the degree of webpage design perfection, and the degree of satisfaction with online reviews. Three measurement items are used to measure the latter: the level of convenience, timeliness, and professionalism of logistics and distribution. Network affinity is measured by the degree of consumers' online search. Due to the multiplicity of risk perceptions of consumers' channel migration of fresh agricultural products, this paper refers to the studies of Jin (2021) and Alrawad et al. (2023). There are a total of five measurement items for risk perceptions: the possibility of economic loss, the possibility of dissatisfaction, the possibility of exposure of personal privacy, the possibility of loss in the transport process, and the possibility of poor service quality (Jin, 2021; Alrawad et al., 2023). There were three measurement items for channel migration behavior: "I am likely to purchase fresh agricultural products from online channels," "I am interested in migrating to online purchases of fresh agricultural products," and "I am willing to recommend the experience of purchasing fresh agricultural products from online channels to others." These variables above were measured using a 5-point Likert scale, ranging from "very low" to "very high," with 1 to 5, and 3 being a neutral option. Network affinity was measured by the degree of consumers' web searching capability, which was also measured by a 5-point Likert scale from "very low" to "very high," with 1 to 5 as the neutral option and 3 being the neutral option. The control variables were age, gender, education level, food safety awareness and household income level of consumers. Age and education level were measured by actual years of experience. Gender was measured by "male = 1, female = 0". Food safety awareness was measured by the Likert 5-level indicator.

3.3 Data sources and sample characteristics

China's online shopping users of fresh agricultural products are mainly in first-tier and second-tier cities, accounting for more than

80% of the fresh e-commerce consumption market (Yan and Zhang, 2022). Harbin is an important central city in the northeast of China, with a large permanent population, large consumption demand and high consumption level. In recent years, the construction of urban fresh e-commerce service platform has made certain achievements, so it has good representativeness. The data in this paper are obtained from the questionnaire survey conducted by the research group in September and October 2023 in the main city of Harbin. The survey sites are mainly concentrated near government agencies, enterprises and institutions, commercial office buildings and residential communities. In view of the research topic of this paper, the survey subjects are set to consumers over 18 years old who have had online shopping experience. The survey is divided into two stages. The first stage is pre-investigation, the members of the research group firstly distributed 50 questionnaires in Xiangfang District of Harbin for pre-investigation starting from early September 2023. The original questionnaire was revised according to the pre-investigation results, to enhance the clarity of the questionnaire. The second stage is the formal investigation. After that, the sample was obtained by random stratified sampling method. The research team selected the 6 main urban areas of Nangang District, Daoli District, Daowai District, Xiangfang District, Pingfang District and Songbei District in Harbin as primary sampling units, then in each main urban area, five streets (towns) were randomly selected according to the level of economic development. Finally, in each street (town), one residential community is randomly selected from each of the five directions: east, south, west, north, and center, three samples are randomly selected from each residential community. The investigators distributed 450 paper questionnaires, 420 questionnaires were recovered, and 416 valid questionnaires were finally obtained, with an effective rate of 92.44%. To ensure the authenticity and validity of the survey data, the questionnaire was completed by trained graduate students and senior undergraduates (Table 1).

The gender of the consumers surveyed is equal in proportion to men and women, with 194 and 222 respectively, this data shows that the gender of the respondents is balanced, representing the perspectives of consumers of different genders. The age of the respondents is mainly 25–40 years old, accounting for more than 65%, this age group constitutes the main body of daily purchases, aligning with the positioning of fresh agricultural products toward the primary consumer demographic. Most of the education is college and above level. The high education level is consistent with the reality

TABLE 1 Descriptive statistics of variables.

Variable types	Variable name	Variable measure	Mean value	Standard deviation
Explained variables	Channel Migration Behavior	I am interested in online channel to buy fresh agricultural products	3.519	1.011
		I have the possibility of buying fresh agricultural products online	3.412	1.124
		I would like to recommend online channel purchase experience of fresh agricultural products to others	3.306	1.136
Core explanatory variables	Feature information	Quality of fresh agricultural products online	3.331	1.025
		Packaging standardization	2.672	1.421
		The integrity of certification	3.214	1.039
	Price information	Price fairness	3.653	1.123
		Price stability	3.801	1.055
		Price preferential intensity	3.699	1.109
	Service information	Professional level of customer service	3.358	1.149
		Web design	3.221	1.139
		Satisfaction of reviews	3.236	1.057
	Logistics information	Logistics convenience	3.119	1.026
		Timeliness	3.374	1.135
		Degree of logistics professionalism	2.968	1.152
Mediating variables	Risk perception	Possibility of economic loss	3.311	1.019
		Possibility of dissatisfaction	3.048	1.322
		Possibility of privacy exposure	2.801	1.031
		Possibility of transportation damage	2.886	1.144
		Possibility of poor service	3.177	1.313
Moderating variables	Network affinity	Degree of consumer' web searching capability	4.082	1.226
Control variables	Age	Actual age in 2023	33.165	8.093
	Gender	male or female	0.466	0.499
	Educational level	Education level	15.732	1.528
	Food safety awareness	Food safety cognition level	3.805	1.189

that online consumers are generally young and high educated. The sample mean for food safety awareness was 3.805, indicating that respondents were generally more concerned about food safety issues. In terms of channel migration behavior of fresh agricultural products, the mean value of each question item is greater than 3, which means that respondents mostly show positive attitudes toward online purchase of fresh agricultural products. The sample mean for network affinity is 4.082, indicating that respondents have a high level of online searching. Overall, the sample composition is reasonable and exhibits good representativeness.

4 Empirical results

4.1 Reliability and validity test

In this paper, SPSS19.0 was used to carry out an exploratory factor analysis on the observed variables. The KMO value was used to test the simple correlation coefficient and partial correlation coefficient between the variables, which can be used as a basis for judging whether the original variables can be applied to factor analysis. A total of six factors were extracted for exploratory factor analysis using orthogonal rotation with maximum variance method. The results showed that the KMO value was 0.841, and the Bartlett's test of sphericity was significant, reaching the significance level of 1‰. The cumulative variance contribution rate was 61.082%, which met the basic requirement of 50%. These can indicate that the structural validity of the questionnaire design of this study is proper and the correlation between the dimensions and the total scale is statistically significant. Meanwhile, this paper uses the Cronbach's α coefficient method to measure the internal consistency between the items in the questionnaire scale. The Cronbach's α coefficient of each item is greater than 0.7, which indicates that the overall reliability level of the questionnaire scale is high. In addition, validity tests generally take the method of validated factor analysis to calculate the standardized factor loading coefficients of each variable. From this, the CR and AVE values of each dimension are derived. The results of the validated factor analysis in this paper indicated that the CR values of all latent variables exceeded 0.7 and the AVE values exceeded 0.5, which can also indicate that the observed variables have better convergent validity and internal consistency.

4.2 Hypothesis testing

4.2.1 The main effect of hypothesis test

According to the conceptual model constructed in Figure 1 of this paper, SPSS 19.0 and AMOS 22.0 software were used to carry out an empirical analysis of the factors influencing consumers' channel migration behavior of fresh agricultural products. Paths were explored for the 416 questionnaire data samples collected, and the results of the path estimation coefficients of the main effects are shown in Figure 2. Each fitting index of the structural equation model meets the requirements and has a good fit, and the test results are not listed here due to space limitations. The coefficient of feature information is significantly positive at the 5% level, which indicates that the feature information of online fresh agricultural products positively influences channel migration behavior of fresh agricultural products, proving that hypothesis H1a is valid. The coefficient of price information is significantly positive at the 1% level, which indicates that the price information of online fresh agricultural products positively influences channel migration behavior of fresh agricultural products, proving that hypothesis H1b is valid. The coefficient of service information is significantly positive at the 5% level, which indicates that service information positively influences channel migration behavior of fresh agricultural products, proving that hypothesis H1c is valid. The coefficient of logistics level is significantly positive at the 10% level, which indicates that logistics information positively influences channel migration behavior of fresh agricultural products, proving that hypothesis H1d is valid.

The standardized path coefficient between feature information and risk perception is −0.263, which passes the test at the 1% level of significance. This suggests that the more comprehensive consumers' information about the features of online fresh agricultural products is, the weaker their risk perception is. The standardized path coefficient between price information and risk perception is −0.322, which is also significant at the 1% level. The higher the price fairness and the greater the discount of online fresh agricultural products is, the weaker the risk perception of consumers is. The standardized path coefficient between service information and risk perception is −0.234, which is significant at the 5% level. The more comprehensively consumers understand service information, the weaker their risk perception is. The standardized path coefficient between logistics information and risk perception is −0.201, which is significant at the 10% level, indicating that the more consumers know about logistics information, the weaker their risk perception is. Therefore, hypotheses H2a~H2d are valid.

In addition, the standardized path coefficient between consumer risk perception and channel migration behavior of fresh agricultural products is −0.316, which is significant at the 5% level. This shows that consumers' risk perception directly affects their channel migration behavior of fresh agricultural products of fresh agricultural products, proving that hypothesis H3 is valid. Nonetheless, risk perception cannot fully explain consumers' channel migration behavior of fresh agricultural products of fresh agricultural products.

4.2.2 The mediation effect of risk perception

Risk perception is the mediating variable in this study. For the test of this variable, we applied the effect test proposed which is widely used in related studies. Based on the Process Bootstrap program, this paper sets the sample size to 1,500, chooses the non-parametric percentile method with bias correction, and sets the confidence level of the confidence interval to 95%. The test results of the mediating effect are shown in Table 2. With risk perception as the mediating variable, in the path of feature information to channel migration behavior of fresh agricultural products, the confidence interval of the Bootstrap test for total effect is (0.405, 0.437); the confidence interval of the Bootstrap test for the indirect effect is (0.051, 0.060); the confidence interval of Bootstrap test for direct effect is (0.288, 0.345). The results above suggest that risk perception plays a partial mediating effect between feature information and channel migration behavior of fresh agricultural products. Similarly, risk perception also plays a partial mediating effect between price information and consumers' channel migration behavior of fresh agricultural products. The same

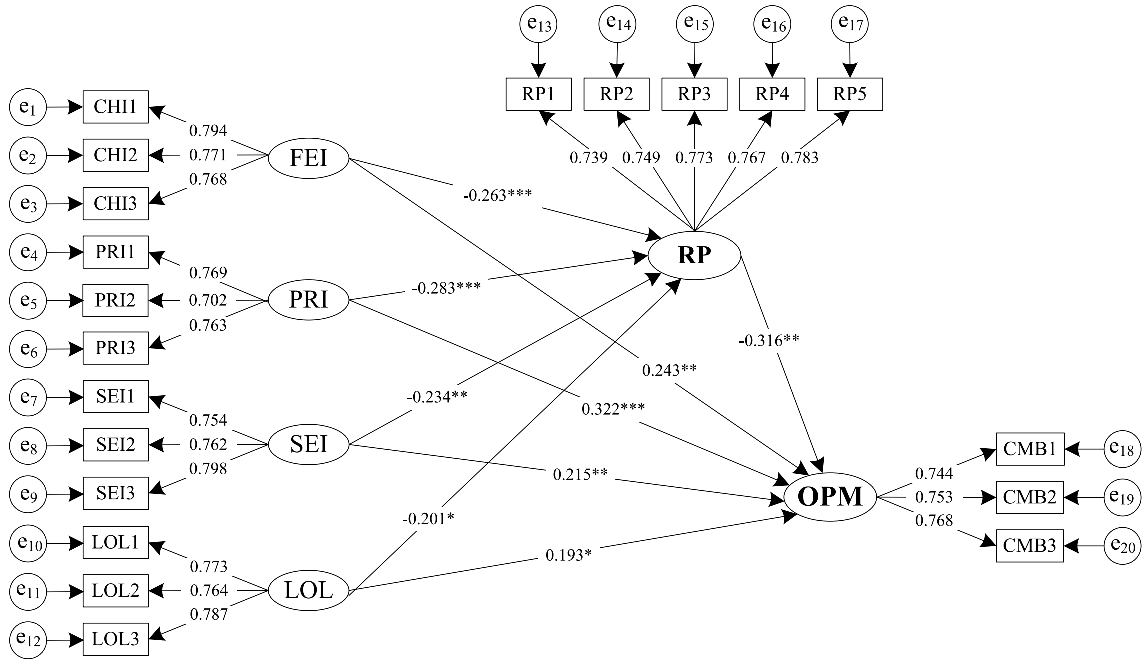

FIGURE 2
The main effect of path coefficient estimates. Note: ***denote $P < 0.01$; **denote $P < 0.05$; *denote $P < 0.1$.

TABLE 2 The mediation effect of risk perception test.

Effect of path	Total effect		Indirect effect		Direct effect	
	Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
FEI → RP → CMB	0.405	0.437	0.051	0.060	0.288	0.345
PRI → RP → CMB	0.388	0.411	0.047	0.058	0.295	0.340
SEI → RP → CMB	0.305	0.381	0.035	0.056	0.243	0.299
LOI → RP → CMB	0.363	0.401	0.027	0.041	0.271	0.313

is true for its effect between service information and consumers' channel migration behavior of fresh agricultural products. It also plays a partial mediating effect between logistics information and consumers' channel migration behavior of fresh agricultural products. In summary, H4a-H4d are validated.

4.2.3 The moderation effect of network affinity

The test of moderating effect has limited application in structural equation modeling, and the method of multi-cluster analysis is mainly utilized in this study. Its principle is to put the sample group before the return path, and then compare and analyze whether there is any difference in the path results, which can also be used for moderating effect analysis. In this paper, the sample consumers are grouped according to high network affinity and low network affinity. The test results of the moderating effect of network affinity are shown in Table 3. When the network affinity is high, the product information and platform information have a positive contribution to reducing consumer risk perception. The standardized path coefficients are 0.141, 0.179, 0.126, and 0.148 respectively, which are significant at the level of 5%, 1%, 5, 5%, respectively. In conclusion, the higher the degree of consumers' web searching capability is, the less risk consumers sense, so network affinity can effectively mitigate the negative effect of risk perception. Therefore, hypotheses H5a–H5d are verified.

5 Discussion

The impact mechanism of consumers' migration behavior of fresh agricultural products is a complex issue, that requires deeper analysis to elucidate how to better promote the migration of fresh agricultural product consumption to online channels. This study took consumers' migration behavior of fresh agricultural products as the research object and explored the relevant factors influencing this behavior. We considered product information and platform information as two key determining factors, this choice aligns with consumers' current shopping habits, as they rarely make decisions based on a single factor but rather tend to consider various aspects of product information and platform information. Based on the SOR model, and form the perspective of information dissemination, we proposed a conceptual model to examine the links between online information, risk perception and consumers' migration behavior in online fresh agricultural products purchases, as well as the moderating effect of network affinity. Among them, online information including product

TABLE 3 The moderation effect of network affinity.

Effect of path	Network affinity	
	Low	High
CHI → RP	0.115 (0.077)	0.141**(0.063)
PRI → RP	0.152**(0.070)	0.179***(0.054)
SEI → RP	0.117*(0.067)	0.126**(0.057)
LOL → RP	0.129*(0.069)	0.148**(0.072)

***$p<0.01$, **$p<0.05$, *$p<0.1$.

information, platform information, and network density are stimuli; risk perception is the body; channel migration behavior of fresh agricultural products is the response. Previous research has mostly emphasized the role of product information and platform information in online channels from the perspective of information dissemination, or highlighted the need to improve consumers' information search abilities. However, they have not examined consumer network affinity from the standpoint of information acquisition as a factor that determines the relationship between online information and risk perception. This paper extends current research and provides theoretical support for the field. At the same time, the study presented in this paper offers a replicable theoretical framework for future discussions on consumer channel migration behavior, enriching the literature on consumer online consumption behavior, and expanding the theoretical research on consumer purchasing channel migration behavior.

According to the study, online information and risk perception are key factors influencing consumers' migration behavior toward online purchases of fresh agricultural products. On the one hand, sound product information and platform information can help to reduce consumers' risk perceptions toward online purchases of fresh agricultural products. The reason is that from the perspective of the capability approach, the rationale for online information to reduce consumer risk perceptions is to enhance consumers' cognitive and choice abilities, which may reduce risk perceptions by fostering a greater sense of understanding and kindness. This expands upon previous research on fresh e-commerce platforms and consumer behavior regarding fresh agricultural products (Cang and Wang, 2021; Guo H. et al., 2022). On the other hand, consistent with many studies, consumers' risk perception is crucial in determining their shifting consumption decisions, and lower risk perception promotes more consumption behavior, this viewpoint aligns with the findings of Munoz-Mazon et al. (2021) and Zhang et al. (2022) regarding consumers' risk perception (Munoz-Mazon et al., 2021; Zhang et al., 2022). As expected, reducing risk perception contributes to a higher chance of consumers' migration to online shopping of fresh agricultural products.

The mediating effect of risk perception reflects how consumers make channel migration behavior of fresh agricultural products of fresh agricultural products based on product information and platform information. This result extends previous research on the mediating effects of risk perception (Zhang et al., 2022), elucidating how product information and platform information influence consumers' channel migration behavior, enriching the study of antecedents and outcome variables of risk perception (Zhang et al., 2022). Overall, this result suggests that online information helps reduce consumer risk perception. If consumers' risk perception is reduced, they will be more likely to turn to online channels to buy fresh agricultural products. This aligns with the findings of Hue et al. (2019), comprehensive online information in online channels can reduce consumers' risk perception, thereby enhancing consumers' willingness to engage in online consumption (Hue et al., 2019). In addition, this verification is practical because it can help fresh e-commerce companies improve product information and platform information on online channels. In the future, fresh food e-commerce companies should further strengthen the construction of online information resources, enhance the depth and experience of online information interaction, and improve the usefulness and effectiveness of information.

The moderating effect enables us to recognize the effect of network affinity between product information, platform information and risk perception. It should be noted that information transmission is a process involving both the supply and demand sides of the market. Effective information acquisition not only requires online sellers to make efforts in information disclosure and transmission, but also depends on whether consumers can obtain this information. This discovery enriches previous research on online consumer behavior by verifying the crucial role of network affinity, and provides empirical evidence for exploring consumer channel migration behavior. In the moderating effect of network affinity, we also find that consumers with high network affinity have a more pronounced effect than those with low network affinity. This result is consistent with a previous study (Wang and Gao, 2020). By emphasizing this difference, it helps to drive research on consumer heterogeneity and extend it to online consumption of fresh agricultural products, thus filling the gaps in previous studies. Future fresh e-commerce can develop differentiated marketing strategies based on the closeness of the consumer network, to better meet the needs of consumers. The research findings of this article can contribute to the sustainable development of online marketing for the e-commerce of fresh agricultural products.

6 Conclusions and suggestions

Online purchase has become the new trend of fresh agricultural products consumption. it is vital to effectively identify the key factors influencing consumers' channel migration behavior of fresh agricultural products of fresh agricultural products and their role mechanisms. Based on the SOR theory, this paper constructs a conceptual model of the factors influencing consumers' channel migration behavior of fresh agricultural products of fresh agricultural products from the perspectives of information acquisition and risk perception. It empirically analyses the factors influencing such behavior and how these factors work by structural equation modeling with 416 valid questionnaires obtained from the field research. The results indicate three conclusions. (1) Product information and platform information significantly affect consumers' channel migration behavior of fresh agricultural products. Product information including feature information and price information has a positive influence on consumers' channel migration behavior of fresh agricultural products. The same is true for such behavior and the platform information including service information and logistics information. (2) Risk perception plays a partial mediating role in the influence of product information variables and platform information variables on consumers' online purchasing and migration behavior of fresh agricultural products. (3) Network affinity negatively moderates the causal relationship between product information and risk perception as well as that between platform information and risk perception. The effect is more pronounced for consumers with high network affinity than consumers with low network affinity.

From the policy point of view, this paper can provide ideas and methods for fresh e-commerce to optimize marketing strategies, so as to promote the economic and social benefits of fresh agricultural products online market and help the sustainable development of fresh e-commerce. We put forward suggestions as follows. First, quality and safety should be ensured and product certification should be improved. It is necessary to improve product quality and safety evaluation standards, strengthen the online market access system, enhance online quality supervision of fresh agricultural products, and establish a sound product certification and quality traceability system to deliver more quality and safety information to consumers. Second, promotions should be increased to attract consumers. The online platform can push coupons to provide discounts and diversified payment methods according to different consumer needs. Third, customer service training should be strengthened to establish a good reputation. Enterprises should cultivate professional online customer service personnel to provide patient and detailed answers, timely processing of quality feedback and after-sales return and exchange services. In addition, improving the after-sales evaluation system and information disclosure system including online feedback is necessary. Fourth, the level of logistics should be improved to realize quality and efficiency improvement. Fresh e-commerce should work on the "last mile" distribution link to facilitate consumers to choose the delivery time and place more flexibly, and online platforms with the conditions can build their own cold chain logistics and distribution centers or build a multi-level and multi-center cooperative distribution system through resource sharing and integration. Finally, the difference in network affinity is a concern. Online shopping knowledge should be popularized to consumers with low network affinity through multiple channels to stimulate their online purchase interest with online purchase advantages. For consumers with high network affinity, online product information should be pushed in time. For example, the more consumers interact with merchants, the greater price discount can be enjoyed to ensure the loyalty and stickiness of these consumers.

This paper constructs a conceptual model of online purchasing migration behavior of fresh agricultural products, and explores how information acquisition and risk perception affect consumers' channel migration behavior of fresh agricultural products, it is helpful to expand the theoretical research on consumer purchasing channel migration. At the same time, the research conclusion provides decision-making reference for improving marketing strategies and expanding online economic benefits, and provides suggestions for the sustainable development of e-commerce of fresh agricultural products. We are committed to providing useful experience and reference for sustainable development of fresh e-commerce in the world, especially for developing countries. There are still some research limitations. First, there are many online consumption platforms for fresh agricultural products, and their target consumer groups also have different characteristics. However, this study has not considered the specific types of online consumption channels for fresh agricultural products. Secondly, the sample consumers of this study are limited to the Main City of Harbin, Heilongjiang Province, but whether the research conclusions have the same applicability for other areas remains to be tested. Finally, the sinking market is expected to be the primary battleground for fresh food e-commerce in the future, so the future research on the growth space for online consumption of fresh agricultural products in cities, towns and rural areas would be helpful.

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.

Ethics statement

Ethical approval was not required for the study involving humans in accordance with the local legislation and institutional requirements. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was not required from the participants in accordance with the national legislation and the institutional requirements.

Author contributions

NC: Writing – original draft, Validation, Funding acquisition. JD: Writing – original draft, Conceptualization. XF: Writing – review & editing, Investigation, Conceptualization. DZ: Writing – review & editing, Methodology, Data curation. ML: Writing – review & editing, Methodology, Data curation. JS: Writing – review & editing, Investigation.

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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.

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EDITED BY
Robert Hunter Manson,
Instituto de Ecología (INECOL), Mexico

REVIEWED BY
Mark Tilzey,
Coventry University, United Kingdom

*CORRESPONDENCE
Andres Suarez
✉ asuarez24@cuc.edu.co

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Transforming food systems in the Global South: a radical approach

Andres Suarez[1,2]* and Chukwuma Ume[3]

[1]Department of Civil and Environmental, Universidad de la Costa, Barranquilla, Colombia, [2]International Ph.D. program in Agricultural Economics, Bioeconomy and Sustainable Food Systems –IPPAE, Justus-Liebig-Universität Gießen, Giessen, Germany, [3]Institute for Agricultural Policy and Market Research, Faculty of Agricultural Sciences, Nutritional Sciences, and Environmental Management, Justus-Liebig-Universität Gießen, Giessen, Germany

Sustainability within food systems (FS) transcends approaches that only consider FS transformation via changing agricultural practices or consumption patterns. The essence lies in addressing the root causes of current unsustainable FS and their associated social and environmental ramifications. This paper aims to outline the solutions needed to revamp these challenges, by paying special attention to the state-capital nexus in the context of the FS'global core-periphery dialectics. Thereby, we embrace radical political agroecology as being essential in promoting sustainability within the FS, especially in the Global South. Agroecology is proposed as the strategy to address the food system's complexity in terms of the social, environmental, and economic embeddedness. We conclude with potential solutions that contribute to the pathway for FS sustainability.

KEYWORDS

critical realism, state-capital nexus, food regime, class struggle, radical political agroecology

1 Introduction

Food systems (FS) are complex webs of processes and products, involving production, processing, packaging, distribution, retail and consumption of food, which finally have implication on social and natural systems (Eliasson et al., 2022). Current challenges of FS arise from several dynamics shaped by capitalist values (Bakker and Gill, 2019). Various authors have highlighted the need to consider social, economic, and ecological outcomes within FS as the starting point in their transformation (FAO, 2019; Giraldo, 2019; Ume, 2023). Others have called for transformative processes in socio-natural relationships, the urgency of shifting mental models, and the need for more democratic and less oligopoly-driven FS (El Bilali et al., 2019; Fanzo et al., 2021; Kugelberg et al., 2021). Achieving sustainability in FS therefore requires addressing root causes and avoiding simplistic approaches. Literature reveals various proposed approaches that emphasize the importance of holistic strategies, innovative collaboration, and systemic transformation (Table 1). Equity, inclusivity, interdisciplinary efforts, and resilience are consistently mentioned priorities that aim to shift paradigms toward more sustainable FS. Yet, there is no universally accepted approach to FS transformations (Juri et al., 2022).

In this paper, we aim to offer an initial guide for approximating FS' transformation toward sustainability, by recognizing their non-linear nature. We reflect on the intricate process of transformation particularly needed in and coming from the Global South to highlight two main points: unequal ecological exchange and peasant resistance. Global North's reliance on extractive practices in the South affects environmental sustainability (core-periphery relation), while Southern peasants play a crucial role in challenging the dominant neoliberal food regime (Tilzey, 2020). We propose a bricolage approach, incorporating various strategies to navigate the complex journey toward achieving more sustainable FS, but from a radical perspective (Tilzey, 2024). By grounding this process in the principles of Critical Realism,[1] we aim to comprehend the root pathways of radical transformation by answering: What is needed to achieve radical FS transformation toward sustainability in the Global South?

2 The nature of radical transformations

Previous studies underscore the nonlinear nature of FS transformation by considering imbalances and the dynamic nature of power in the agricultural sector (Kok et al., 2019; Eliasson et al., 2022). According to Eliasson et al. (2022) confronting the inherent power structures across geographical scales and promoting social movements advocating for food sovereignty are important. Collective understanding and agency are also deemed crucial for creating more sustainable FS. Examining structural and agential aspects in FS transformation through the lens of Critical Realism is also important for understanding to understand the dialectics of socio-natural relations in FS (Tilzey, 2018). Following the critical realist Transformational Model of Social Activity (Bhaskar, 2008), this paper seeks to reveal the interplay between social-natural-agrarian structures and human agency as a "structured agency" (Potter and Tilzey, 2005). The approach posits that social structures influence human actions, which, through social interactions, can reproduce or transform these structures. Critical Realism provides a comprehensive framework for navigating the complexity of FS transformation through human agency, by considering material transactions with nature, social interactions, social structure, and individuals' inner being (Bhaskar, 2008; Buch-Hansen and Nesterova, 2023). This wide insight into the FS posits that its essence is profoundly interconnected across these 4 dimensions. Acknowledging and actively

1 Critical realism is a philosophical framework that seeks to understand the underlying structures and mechanisms that shape reality. It acknowledges the that our knowledge of this reality is mediated through our social context (Danemark et al., 2019). For this paper, critical realism is key because this approach seeks human emancipation by providing tools to analyze and critique existing social structures and systems of power.

TABLE 1 A mini review of literature related to FS transformations.

Author	Requisites for FS transformations toward sustainability
Anderson (2015)	Sustainable food systems necessitate healthy soil, clean water, skilled farmers, secure intergenerational resource transfer and knowledge, as well as dispersed, decentralized food and energy production.
Kok et al. (2019)	Scaling agroecological practices, co-producing local knowledge in organic agriculture, fostering collaboration in technology development, and co-designing governance strategies with small-scale fisheries are key for sustainability.
El Bilali et al. (2019)	Enhancing efficiency (e.g., sustainable intensification), promoting demand restraint (e.g., sustainable diets), and transforming food systems (e.g., alternative systems) are crucial. This involves promoting healthy consumption, scaling up innovations, optimizing yield, encouraging agro-ecological practices, diversifying farms, and advocating landscape approaches in supply chains.
Dupouy and Gurinovic (2020)	Coordinated interdisciplinary changes, including nutrition-sensitive agriculture, increased investments in research and innovation, promotion of dietary change, and the shift toward circular economies. The goal is to facilitate stable and healthy diets amid the ongoing structural transformation of food and agriculture.
Ridolfi et al. (2020)	Transforming food systems is a complex process, requiring an integrated systemic approach to avoid narrow technical fixes and recognize trade-offs amid diverse challenges in achieving multiple outcomes.
Ruben et al. (2021)	Shift from food security to system resilience, combining efficient production with affordable nutrition, inclusive livelihoods, and sustainability. Improve connectivity and responsiveness, transitioning to circular food systems. Anchor governance through integrated approaches, moving beyond targeted incentives.
Fanzo et al. (2021)	Addressing diets and health, environment and climate, livelihoods and equity, governance, and resilience.
Levkoe (2021)	To foster equity and sustainability in food systems, it is essential to examine diverse factors contributing to inequity and understand how power operates across different regions, even when these issues may seem unrelated initially.
Niewolny (2022)	The key focuses encompass agroecological research, policy formulation, worker protections, intersectional food justice scholarship, narrative-led methodologies, and multi-sector coalitions challenging conventional practices.
Sonnino and Milbourne (2022)	The central themes include the socio-natural composition of place, the positive interactions and connections forming spatial identity, the social processes (including power dynamics) influencing everyday spatial practices, and the flows of ideas, materials, people, and resources transcending space.
Patay et al. (2023)	The key concepts involve the socio-natural composition of place, positive interactions shaping spatial identity, social processes influencing everyday spatial practices, and the crosscutting flows of ideas, materials, people, and resources.
Eliasson et al. (2022)	Essential elements include the Paradigm (encompassing goals, governance, information, knowledge, infrastructure, and mindset), Targets (concrete formulations and objectives), Governance (rules and power for system change), Information and Knowledge (flows, production, traceability, transparency), and Infrastructure (physical elements and connections).
Zhu et al. (2023)	The transformation paths for the food system involve establishing a globally beneficial, cleaner, and fair participatory system, enhancing innovation capabilities, and implementing an effective organizational guarantee system.

addressing this interconnected nature enhances the potential of radical transformative initiatives to foster sustainable changes.

Since FS unfold in these four dialectically interrelated dimensions of human agency, it is essential to determine the origin of the causal mechanisms that lead to discrepancies across these four planes. This comprehension introduces even greater complexity, specifically, when considering the open and multi-scaler nature of social-natural-agrarian systems, which requires a layered explanation (Collier, 2013). According to Bhaskar and Danermark (2006), layered systems pertain to multiple levels of reality organized on a hierarchical scale. In such systems, it is possible to delineate distinct levels of agency and collectivity. Explanations within layered systems involve mechanisms at various of these levels. This involves understanding comprehensively all aspects of society and not only what and where things happen, as represented by the four-planar social being, but also exploring how and why they occur (causal mechanisms), as depicted in the multi-scalar social being (Figure 1).

While various approaches aim to provide guidance for achieving sustainability transformations in food systems, (Table 1) it is crucial to recognize that the complexity inherent in this transformation (Figure 1) requires a comprehensive perspective, and in our case, a radical one. We will navigate the intricacies discussed earlier by examining the instance of FS in the Global South.

3 A layered approach for analyzing FS transformations

The recognition that social-natural-agrarian phenomena unfold across the four dialectically interrelated planes provides a comprehensive framework for understanding FS transformations. Recognizing transactions with nature, social structures, social interactions, and deep personality enables a nuanced understanding of the scenario where mechanisms behind FS unsustainability across various scales emerge (Table 2). Therefore, the challenge is to address transformations in the myriad of scales that produce unintended and unsustainable consequences in global FS occurring in the four planes throughout multiple scales.

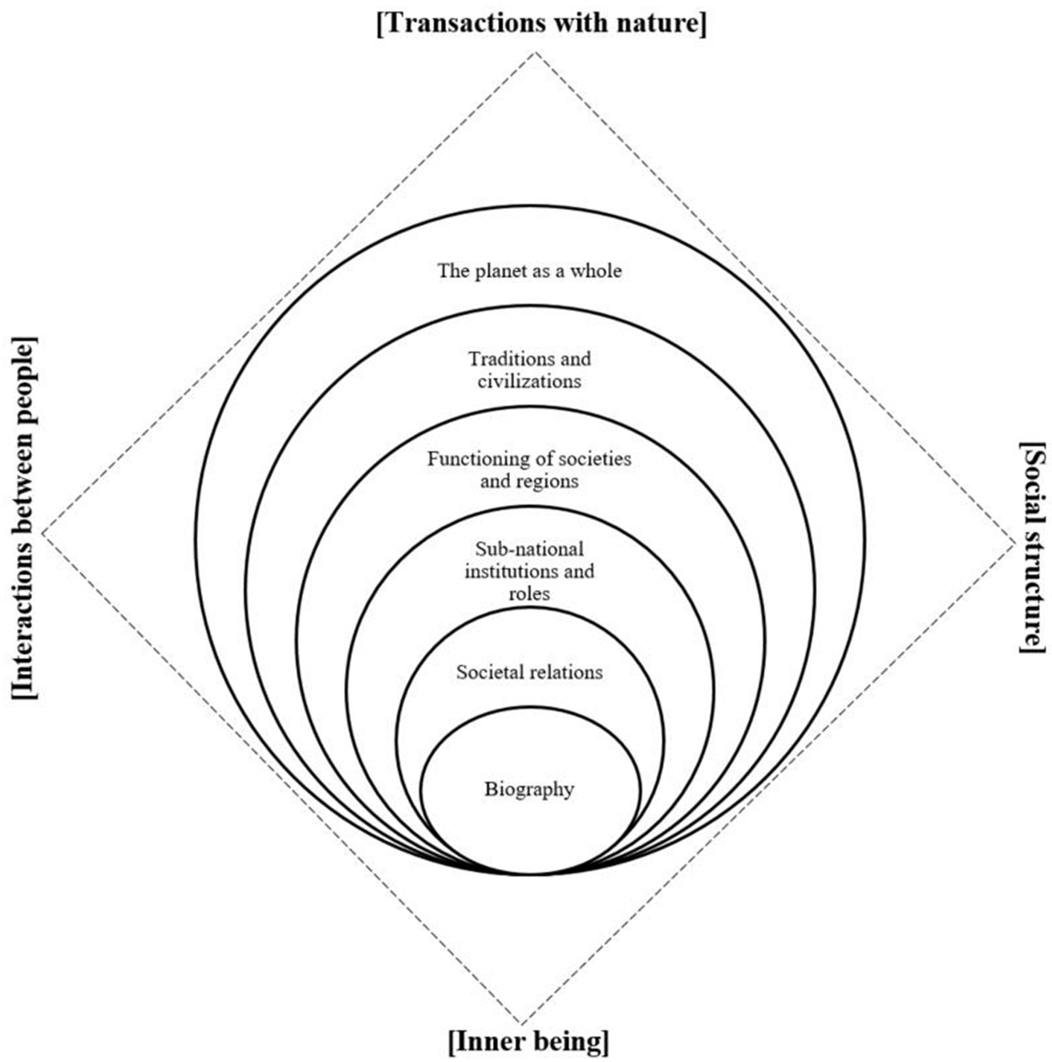

FIGURE 1
Four planar and multi-scalar social being (Bhaskar and Danermark, 2006).

TABLE 2 Complex emergent problems of FS in the Global South.

Scale	Characteristic current food system
The planet as a whole	Global capitalism, globalization of FS
Traditions and civilizations	Neoliberal food regime
The understanding entire societies or regions functioning	Waves of colonization
Sub-national institutions and functional roles	Neo-liberal agriculture, policy oriented toward agroextractivism
Social relations	Master–slave relations, patronage, inequality
Individual or biographical level	Personal experiences dealing with market-oriented FS

The structural framework enabling and constraining human agency on the four planes when analyzing contemporary FS consists of the complex state-capital nexus, which acts as the primary source of legitimation and enforcement by facilitating capital accumulation through varying degrees of mediation (Tilzey, 2020; Tilzey and Sudgen, 2024). This structure enables the intricate web of the global economy, where the world is starkly divided into dialectical imperial-peripherical relations; i.e. the Global North pressures the socio-natural systems of the Global South (Tilzey, 2020). Large-scale corporations (supported by the state-capital nexus), wielding immense power, spearhead the production and commercialization of commodities (Tilzey, 2024). The deeply rootef historical legacy of colonization lingers, perpetuating extractive activities in the agricultural sector (McKay et al., 2021; Petras and Veltmeyer, 2023). National, regional, and municipal policies, rather than nurturing local initiatives, fuel the relentless expansion of commodity cultivation (Veltmeyer and Lau, 2020). Amidst this backdrop, non market-oriented peasantry (c.f. Tilzey, 2024) find themselves marginalized, overshadowed by the preeminence of corporate growers, with a surge in land grabbing and rural proletarianization exacerbating their plight (Tilzey and Sudgen, 2024). In the midst of these dynamics, plantations become arenas of conflicted experiences, where individuals navigate through a process of apprehension, particularly in the Global South (Suarez and Gwozdz, 2023). Meanwhile, in the Global North, a personal quest for healthy and trendy diets further complicates the intricate tapestry of global agricultural dynamics.

4 Toward FS sustainability

4.1 Radical transformations

The transformations needed in the four-planar social being of current FS could be rooted in the principles of agroecology[2]. As underscored by Botelho et al. (2016), agroecology emerges as a strategic agenda for restructuring prevailing models of agricultural development. It has evolved into an encompassing framework for advancing FS, strategically addressing the interconnected social, economic, and environmental challenges inherent in current dominant systems (Coe and Coe, 2023). However, agroecology has undergone co-optation processes (Biel, 2016a; Walthall et al., 2024), therefore its proposal must manifest clear positionalities.

In order to outline pathways toward a radical FS transformation, our approach must be based on aspects that support such radicality. Thus, our positionality is based on a counter-hegemonic approach (Tilzey, 2016, 2024), which differs from other positions that also embrace agroecology as a transformative strategy (c.f. Tilzey, 2024). Following Tilzey (2024), we stress that FS transformations needed in the four-planar social being could be rooted in radical political agroecology. Here, reversing the causal mechanism of unsustainable FS embodied by the state-capital nexus depends on “class struggle” acting as a structured agency that challenges both the discursive and material predicates of capitalism (Tilzey, 2016, 2018). In this sense, an important driver of transformation in the Global South is the middle and low peasantry,[3] which, through processes of resistance (prioritizing use values over exchange values), can mobilize FS transformations, and prevent co-optation within existing hegemonic FS social-property relations (Tilzey, 2018).

Once this counter-hegemonic positionality is clear, we emphasize how an agroecological approach, driven by the organized efforts of the middle and low peasantry in the Global South, can facilitate significant transformations across the four dimensions of social being (Figure 1). First, at the level of social structures, the structured agency of middle and lower peasants can counteract the centralized, top-down approach in which society and production are organized by elites through class struggle (Biel, 2016a,b). Here, the radical transformative approach must reckon not only with capitalism (social-property relations and access to land) and neoliberalism (market compulsion), also with the entire history of exploitation, particularly in FS (Biel, 2016b), which overlap with the state-capital nexus (Tilzey, 2019).

In the plane of *transactions with nature*, if ecological degradation produces class struggle (Vlachou, 2004), then class struggle can also confront the capitalist roots of current ecological threats (Shantz, 2004). One way to subvert this dynamic is by promoting agroecological principles and practices, which have shown efficacy in promoting biodiversity-based agriculture (Duru et al., 2015a,b). Beyond this, agroecology also seeks to address *social interactions*, including considerations of gender (Ume et al., 2022), liberation from oppressive relations (Bezner Kerr et al., 2019), and the enhancement of skills, knowledge, work capacity, and health. Furthermore, agroecology, as emphasized by Coe and Coe (2023), supports transitions in thought. Involving the *inner being*, refers to non-material factors intertwined with culture, values, ethics, identity, and emotions. Some authors argue that the practice of agroecology leads middle and low peasants to strengthen their religious beliefs and redefine personal relationships with the natural and social environment (Botelho et al., 2016).

2 Agroecology is the proposition that agroecosystems should strive to replicate the biodiversity and functioning of natural ecosystems. However, agroecology suggests more than agricultural practices by including social resistance and subverting the state-capital nexus (Tizley, 2024).

3 One of Tilzey's (2024) criticisms of other approaches promoting agroecology is the lack of differentiation of the peasant class. There, Tilzey proposes low, middle and upper peasants that have different characteristics and positions in resisting the state-capital nexus.

4.2 Radical solutions needed

Transformation in FS requiere multifaceted mechanisms (Gupta et al., 2021), particularly those challenging the current state-capital nexus (Tilzey, 2024). We explore six different radical-solutions through the lens of the multi-layered scale (Figure 1). The identified solutions are interconnected components of a comprehensive strategy for transforming FS.

First, it is important to advocate for a diversified and locally adapted FS that promotes healthier diets and involves recognizing the inherent class struggle within the current global FS (Biel, 2016a; Tilzey, 2018). This advocacy inherently challenges the dominance of capitalist interests prioritizing profit over people and planet, and encourages policies and initiatives that prioritize indigenous and sustainable food sources (Agrawal et al., 2021) and represents a form of counter-hegemonic resistance against the prevailing narrative of globalized and resource-intensive crop production, that often exploits both labor and natural resources for the benefit of capitalist elites (Biel, 2016b; Tilzey, 2024). Second, struggles for regulations and incentives to support decentralized and community-based (use-value oriented) agricultural models further disrupt the core-periphery dynamics perpetuated by capitalist exploitation, allowing low and middle peasantry to control their own means of production (Tilzey and Sudgen, 2024).

Third, addressing historical injustices through land reform policies acknowledges the legacy of colonialism and imperialism, that systematically marginalized and exploited indigenous peoples and peasants (Scheidel et al., 2024). The prioritization of sustainable agricultural practices focusing on soil health, biodiversity, and community well-being challenges the capitalist logic of endless growth and profit (Veltmeyer and Lau, 2020), and lays the groundwork for more equitable and resilient FS. Fourth, struggles for policy changes that prioritize diversified and locally driven agricultural practices amplify the voices of marginalized communities and challenge the dominance of corporate interests in shaping agricultural policies (Sargani et al., 2020).

Five, strengthening land rights for low and middle peasantry is crucial for preventing further dispossession and promoting sustainable and equitable land use (Nyantakyi-Frimpong and Bezner Kerr, 2017; Akram-Lodhi et al., 2021; McKay et al., 2021). Finally, promoting agroecological practices that integrate environmental sustainability with local dietary needs challenges the dominant paradigm of industrial agriculture (Agrawal et al., 2021), which favors monoculture and chemical inputs at the expense of environmental and human health (Biel, 2016a). Educational programs and awareness campaigns empower consumers to make informed choices supporting local and sustainable FS, thereby challenging the dominance of corporate agribusiness in shaping consumer preferences.

5 Discussion

Literature on scaling-up agroecology have reported various additional challenges. Some authors emphasize the need to recognize agroecological systems as systems in transition, and that supportive policies are required to scale up agroecology (Dumont et al., 2021). Similarly, scaling-up agroecology requires understanding constraints at the farmer level, an agricultural knowledge system favoring mainstream approaches, adverse and intertwined political and economic interests, and cross-cutting ideological and discursive pressures (Isgren, 2016). Other aspects that requires attention are insecure land tenure and unequal access to land, unequal systems of exchange, and a culture that favors silver bullet narratives (Jiménez-Soto et al., 2024). To attain sustainable FS, it is important to explore diverse solutions while acknowledging their interconnected components. This entails embracing radical transformation through a counter-hegemonic stance (Tilzey, 2024). This approach is crucial for comprehending root problems, such as the pervasive state-capital nexus, and the development of the green revolution paradigm and its discourses (Mier y Terán Giménez Cacho et al., 2018).

Drawing on this counter hegemonic positionality, we emphasize the need to confront power structures through class struggles embedded in FS advocating for food sovereignty (Biel, 2016a; Tilzey, 2018, 2020, 2024; Tilzey and Sudgen, 2024). Such emphasis puts a spotlight on power dynamics within FS and addressing the unequal distribution of resources and the marginalization of certain groups. Recognizing power imbalances highlights the crucial role of agroecology in challenging these power dynamics though processes immbicated in class struggles, promoting fairer access to resources and inclusive decision-making processes. We expand on this narrative by highlighting the significance of social movements in fostering transformation. We argue that agroecology goes beyond ecological practices and encompasses a socio-political dimension (Biel, 2016a). Social movements advocating for food sovereignty though class struggle, align with agroecological principles by seeking to empower local communities, challenge corporate dominance, and promote participatory decision-making in food production.

6 Recommendations

Conflicted dynamics reflecting the tensions between economic motivations, health-conscious consumer trends, and environmental sustainability. These tensions underscore the complexities inherent in transforming FS, highlighting the need for a comprehensive approach. This perspective paper contributes to the broader literature on food systems' transformation by providing guidelines rooted in Critical Realism and the four-planar and multi-scalar social being framework. By acknowledging the interplay between social-natural-agrarian structures and human agency as a structured agency (Potter and Tilzey, 2005), our proposal provides a theoretical foundation for navigating the intricate journey toward sustainable food systems.

In this vein, and acknowledging the transformative role of the peasantry in the Global South due to their dynamics of constant resistance and social reproduction (prioritization of use values over exchange values), we offer recommendations that must necessarily be grounded in a dialectical process. Through class struggle and the subversion of center-periphery dynamics, this process enables the construction of pathways that contribute to more sustainable FS.

- Promote Agroecological Principles: building on the agroecological framework discussed, advocate for adopting practices that integrate environmental sustainability with local and global food needs.
- Advocate for Local Empowerment through Policy Reforms: extend the paper's call for policy changes to various governance

levels, prioritizing diversified and locally driven agricultural practices, thus empowering low and middle peasantry.
- Secure Land Rights for Sustainable Agriculture: addressing historical injustices, champion strengthened land rights for local communities, countering land grabbing and dispossession, and rectifying past exploitation.
- Challenge Corporate Dominance in Agriculture: corresponding to the paper's recommendations, lobby for regulations favoring decentralized agricultural models, ensuring fair profit distribution, and implementing policies that prioritize local farmers over large corporations.
- Foster Global Collaboration for Dietary Sustainability: engaging in efforts to counter pressures from the global North's push for resources. Advocate for policies prioritizing indigenous and sustainable FS, thus fostering a global shift in dietary habits and challenging the core-periphery logics.

Collective efforts dentify and address potential weaknesses in the proposed approach is essential. One concern is the feasibility of implementing recommended strategies across diverse socio-political regimes. While advocating for agroecological principles and local empowerment through policy reforms is crucial, future research should delve deeper into challenges such as resistance from entrenched interests, bureaucratic hurdles, and the need for substantial financial and technical support to facilitate meaningful change.

Considering the long-term sustainability and scalability of proposed solutions is crussial, given factors like the state-capital nexus, market changes and climate variability. Future research should investigate these aspects to ensure effectiveness. Additionally, exploring unintended consequences of challenging neoliberal dominance in agriculture is essential, requiring careful consideration of supply chain disruptions and socio-economic impacts. Through empirical research, valuable insights can enhance the proposed approach's robustness and applicability.

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

AS: Writing – review & editing, Writing – original draft. CU: Writing – review & editing.

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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.

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National Institute of Agricultural Extension Management (MANAGE), India
Isaac Oluwatayo,
University of Venda, South Africa

*CORRESPONDENCE
Mohammad Jahangir Alam
✉ alambau2003@yahoo.com

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The effect of total factor productivity on the food security and livelihood vulnerability of farm households in Bangladesh

Paresh Kumar Sarma[1], Mohammad Jahangir Alam[1]*, Ismat Ara Begum[2] and Andrew M. McKenzie[3]

[1]Department of Agribusiness and Marketing, Bangladesh Agricultural University, Mymensingh, Bangladesh, [2]Department of Agricultural Economics, Bangladesh Agricultural University, Mymensingh, Bangladesh, [3]Department of Agricultural Economics and Agribusiness, University of Arkansas, Fayetteville, AR, United States

Food security and livelihood vulnerability are important issues for the economic sustainability of developing countries like Bangladesh. This study examines the influence of total factor productivity (TFP) on the livelihood vulnerability and food security of rice farming households in Bangladesh. Data from 1,841 rice farming households were extracted from the Bangladesh Integrated Household Survey (2015 and 2018) conducted by the International Food Policy Research Institute. Various statistical methods, such as the stochastic frontier model, principal component analysis, path analysis using structural equation modeling, and multivariate regression, were employed to analyze the data. The study utilizes a multivariate modeling approach that combines the stochastic frontier model to determine TFP and sophisticated methodologies to estimate the livelihood vulnerability index (LVI) and women's empowerment in agriculture index (WEAI). The LVI, household dietary diversity Score (HDDS), TFP, and WEAI scores were 0.454, 10.72, 0.703, and 0.717, respectively. The results indicate a significant relationship between TFP and both LVI and HDDS. Higher TFP is associated with lower LVI and higher HDDS among rice farming households, suggesting that improving TFP can enhance food security and reduce vulnerability. The multivariate regression analysis reveals that TFP, household wealth index, women's empowerment in agriculture index, *per capita* food expenditure, household level welfare, and household size have a positive significant impact on HDDS, while TFP is negatively associated with LVI, *per capita* food expenditure and household size. The findings underscore the importance of increasing TFP to improve food security, reduce livelihood vulnerability, and achieve sustainable development goals in countries like Bangladesh. Higher TFP yields positive outcomes regarding household dietary diversity and livelihood vulnerability, highlighting the need for agricultural policies that prioritize TFP enhancement. Policymakers and professionals can use these findings as a roadmap to implement advanced agricultural policies to achieve food security and reduce livelihood vulnerability. Improving household dietary diversity and reducing livelihood vulnerability can be achieved by focusing on increasing TFP, enhancing household wealth, women's empowerment, *per capita* food expenditure, household welfare, and household size. Therefore, increasing TFP should be considered in the design of policies aiming to achieve SDGs Goal 2.

KEYWORDS

climate vulnerability, dietary diversity, farm efficiency, total factor productivity, Bangladesh

1 Introduction

Bangladesh is primarily an agricultural country, and agriculture is critical to the country's rapid economic growth. Rice is Bangladesh's most important food crop, accounting for 75% of the cultivated area (Ganesh-Kumar et al., 2012) and providing 48% of rural employment, half of agricultural GDP (13.10% of total GDP), and approximately 75% of calories and 55% of protein consumed (Bhuiyan and Paul, 2004). In 2020, Bangladesh produced 465 million metric tons of rice on approximately 158 ha of land. Despite the COVID-19 pandemic, rice production has increased by approximately 38.70 million metric tons with the help of timely governmental initiatives. The present government has undertaken several innovative actions to further increase rice production (by 47 million metric tons by 2030, by 54 million metric tons by 2040, and by over 60 million metric tons by 2050) by minimizing the effect of natural and environmental disasters, including cyclones and floods (Ahmed, 2021). Furthermore, Bangladesh's economy is a developing consumer economy, with a nominal GDP of USD 39 billion and a purchasing power parity of USD 29 billion (WFP, 2009; Raiz and Rahman, 2016; Villoria, 2019). However, it is confronted with major problems, including food insecurity. Despite the fact that the country has achieved food self-sufficiency, food insecurity affects a considerable number of people in the country. Over the next 30 years, rice output (a major crop in Bangladesh) is expected to have tripled (Nazma and Saiful, 2012; Hossain and Riad, 2021). Rice is the most consumed food in Bangladesh, accounting for more than 70% of people's daily calories (Magnani et al., 2015). As a result, rice production self-sufficiency has become synonymous with food security (Bishwajit et al., 2013). Bangladesh has abundant quantities of key food crops, particularly rice, which is the country's staple diet (Nazma and Saiful, 2012; Hossain and Riad, 2021). Food security is a global issue affecting all of us, with one out of every nine people going hungry every day (WFP, 2020). Additionally, 2 billion people around the world suffer from hunger owing to micronutrient shortages such as iron, vitamin A, and zinc (Ritchie et al., 2018). In Bangladesh, where overcrowding and the deteriorating interaction between land and humans (Nazma and Saiful, 2012) is making food security a major priority, food insecurity is particularly acute (Parvin and Ahsan, 2013).

The ratio of total agricultural production to the total input of land, labor, capital, and materials used in agricultural production is known as total factor productivity (TFP). An increase in TFP indicates that the growth rate of total production is faster than the growth rate of total input use. TFP will vary based upon the efficiency with which inputs are transformed into outputs. Several studies have claimed that technological efficiency (TE) and the extension of cultivable areas, rather than a technological shift, are the primary contributors to TFP in agriculture (Mullen, 2007; Block, 2010; Seaward, 2016). Previous research has mostly employed cross-sectional data and the stochastic frontier approach to measure TFP at the local level (Alemu et al., 1999; O'Donnell, 2008; Christopher and O'Donnell, 2012; Wassie, 2019). Only a few studies (Alam et al., 2011; Suphannachart, 2013; Kondo et al., 2017) have examined the TFP of rice in Bangladesh, and none have examined its impact on food security and livelihoods. We seek to shed light on this important issue by analyzing the relationship between TFP, food security, and livelihood vulnerability. We find empirical evidence showing that increases in TFP contribute to food security and reduce livelihood vulnerability in Bangladesh. Our results highlight the importance of formulating policies that enhance TFP to alleviate hunger and achieve food security in Bangladesh. The study's novelty lies in its focus on analyzing the TFP of rice farming households in Bangladesh and its direct impact on food security and livelihood vulnerability. While previous studies have examined TFP in relation to agriculture, there is limited research specifically on TFP in the context of rice farming and its implications for food security and livelihood stability. To address this gap, our study adopts a multivariate modeling approach that combines a stochastic frontier model to determine TFP, along with sophisticated methodologies to estimate the LVI and WEAI. By integrating these variables and methodologies, our study provides a comprehensive analysis of the interactions between TFP, food security, and livelihood vulnerability, offering new insights into the relationships within the context of rice farming households in Bangladesh.

The remainder of the paper is organized as follows. Following this Introduction, Section 2 presents the conceptual framework followed by the methodology adopted in this study in the Section 3. The results are presented Section 4 and discussion is in Section 5. Finally, Section 64 provides the conclusions, including policy implications.

2 Conceptual framework

The conceptual framework (*CF*) provides a structured approach to understanding how specific interventions lead to desired outcomes. In the context of total factor productivity (TFP) and its impact on food security and livelihood vulnerability among rice farming households in Bangladesh, the *CF* illustrates how improving TFP can positively affect these variables. The study revealed significant relationships between TFP and indicators such as the HDDS and LVI, indicating that TFP improvements directly influence these variables.

Based on previous studies (Reddy, 2016; Dinesh et al., 2021; Reddy et al., 2022), Figure 1 shows that the graphical representation of the *CF* illustrates how TFP impacts both HDDI and LVI. Increasing TFP through modern technologies and better management practices enhances agricultural efficiency, leading to improved HDDS and decreased LVI. Conversely, decreased TFP has adverse effects. To enhance food security and livelihoods, interventions should focus on boosting TFP through measures such as agricultural training, technology access, infrastructure development, and market integration. These initiatives increase productivity, stabilize incomes, and diversify diets, ultimately enhancing the well-being and resilience of rice farming communities. Livelihood vulnerability is influenced by various factors, including human capital, natural capital, social capital, and financial capital of households or individuals (Liu et al., 2024). Livelihood strategies are considered key determinants of livelihood vulnerability. Households engaged in agriculture or other informal occupations, compared to those with members in government jobs, have lower HDDS, suggesting higher LVI (Kundu et al., 2021). Additionally, households with members suffering from chronic illness also experience higher levels of food insecurity and lower HDDS, indicating increased livelihood vulnerability (Dirghayu et al., 2023). This demonstrates an inverse relationship between livelihood vulnerability and household dietary diversity. Households

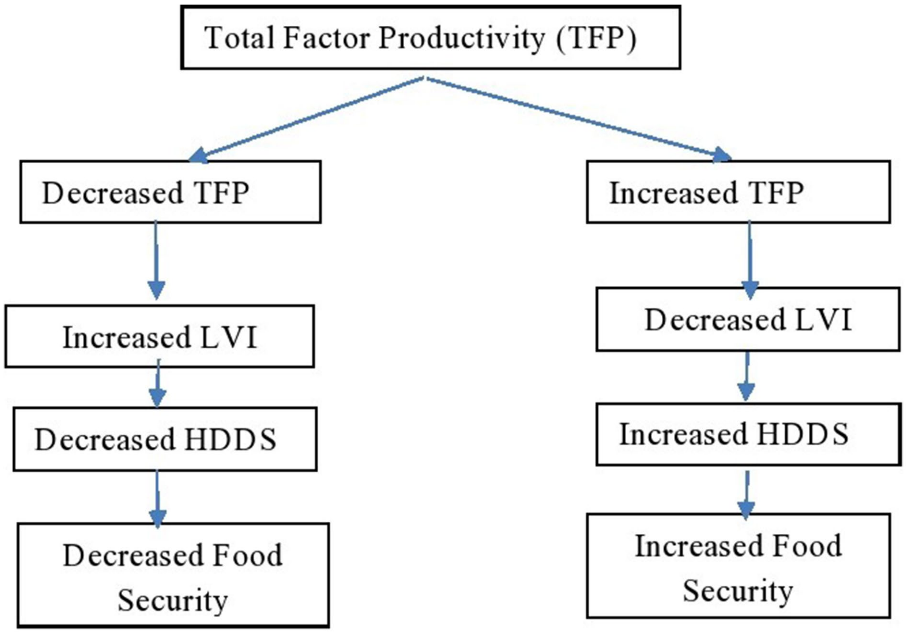

FIGURE 1
Conceptual framework: pathways to increase food security and livelihoods.

facing higher livelihood vulnerability, characterized by socioeconomic disadvantages, tend to exhibit lower dietary diversity scores, suggesting reduced access to various foods. The conceptual framework presents an understanding of the pathways and mechanisms through how TFP impact food security and livelihoods. TFP, which reflects the efficiency of resource use in production, can influence households' overall productivity and economic well-being. Conversely, LVI provides insights into the susceptibility of households to external shocks and stresses, highlighting areas where interventions are needed to enhance resilience. The HDDS is crucial for assessing households' nutritional status and food access, directly impacting their food security. Moreover, the study emphasizes the significance of factors such as women's empowerment, access to social safety nets, and wealth index in TFP analysis. Integrating these factors into the framework ensures a comprehensive understanding of the pathways toward achieving desired outcomes. Policymakers and stakeholders can utilize this study as a roadmap for implementing advanced agricultural policies in Bangladesh and similar contexts.

3 Methodology

3.1 Data source

The study used the 2015 and 2018 Bangladesh Integrated Household Survey (BIHS) administered by the International Food Policy Research Institute (IFPRI). Data for 1,841 rice farming households were extracted from a total of 5,603 households. The BIHS provides nationally representative household survey data. The IFPRI dataset is publicly available. The study used the IFPRI dataset and hence did not require the approval of an institutional review board.

3.2 Variable description and assumptions

The measurements of response and predictor variables, as well as their *a priori* expected signs according to economic theory, are presented in Table 1.

3.3 Econometric methods

The impacts of TFP on rice farmers' HDDS and LVI are examined using a mix of three econometric methodologies. First, a stochastic frontier model was used to determine the TFP. Second, we used the method of Hahn et al. (2009) and Alkire et al. (2013) to estimate the LVI and WEAI, respectively. A multivariate regression model was utilized in the third stage, with LVI and HDDS as response or outcome variables, which are explained by TFP and other predictor variables listed in Table 1.

We measured TFP at the farm level as the residual from the production function (Baily et al., 1992; Neil et al., 1992; Bartelsman and Dhrymes, 1998; Şeker and Saliola, 2018). We estimated household TFP as a multiplicative combination of change in technical efficiency (EC) and technical change (TC), where TE is:

$$TE_{it} = E\left[\exp\left(-U_{it}\right) / \left(V_{it} - U_{it}\right)\right] \qquad (1)$$

Equation (1) can be used to compute the TE of production for the ith farm in the tth year (Coelli et al., 2005). Here, V_{it} are the error components that are uncorrelated with the regressors, and U_{it} are the non-negative variables associated with technical inefficiency in production.

EC_{it} can be expressed as follows in Equation (2):

TABLE 1 Description of response and predictor variables.

	Definition	Expected sign
Response variables		
HDDS	The household dietary diversity score (HDDS) is a composite continuous variable. It is measured as per Food and Agriculture Organization (FAO) guidelines. Its score ranges between 0 and 12. The HDDS is used to represent food security status; higher scores correlate with a better nutrient intake.	
LVI	The livelihood vulnerability index (LVI) is a continuous variable which is measured following methodology of Hahn et al. (2009).	
Predictor variables		
WEAI	The Women's Empowerment in Agriculture Index (WEAI) is measured using the Alkire–Foster method. The WEAI score ranges between 0 and 1. A score greater than 0.8 indicates empowerment. In our model, the WEAI is a binary variable (empowered = 1, and 0 otherwise).	+
TFP	Total factor productivity (TFP) is a composite variable. It is measured using a stochastic frontier model.	+
PCFEP	*Per capita* food expenditure (PCFEP) is a binary variable (food-secure household = 1, and 0 otherwise).	+
HWF	Household welfare (HWF) is a continuous variable measured in terms of *per capita* non-food expenditure (in Bangladesh Taka).	+/−
ASSNT	Access to social safety net (ASSNT) is a binary variable (access = 1, and 0 otherwise).	+/−
Occup	Occupation (Occup) is a binary variable. If the main occupation is farming it takes the value of 1, and 0 otherwise.	+/−
Hsize	Number of people in a household.	+/−
HWI	The household wealth index (HWI) is a continuous variable.	+

$$EC_{it} = \frac{TE_{it}}{TE_{is}} \tag{2}$$

where $TE_{it} = d_0^1\left(X_{it}/Y_{it}\right)$ and $TE_{is} = d_0^{1s}\left(X_{is}/Y_{is}\right)$.

Here, the notation $d_0^1\left(X_{it}/Y_{it}\right)$ represents t period observations and $TE_{is} = d_0^{1s}\left(X_{is}/Y_{is}\right)$ represents s period observations. X_{is} denotes the input variables.

TC quantifies the change in the border input distance function, regardless of where the input distance functions for states outside the frontier are located, as expected. The index of technical change (TC_{it}) can be derived directly from the estimated parameters of the stochastic production frontier model between two neighboring periods s and t. The partial derivatives of the production function are evaluated with respect to time at X_{it} and X_{is}. The geometric mean is calculated after converting these into indexes. The technical change index is calculated as follows in Equation (3), following Coelli et al. (2005):

$$TC_{it} = \left\{\left[1 + \frac{\delta \int\left(X_{is}, S, \beta\right)}{\delta S}\right] X \left[1 + \frac{\delta \int\left(X_{it}, S, \beta\right)}{\delta S}\right]\right\}^{0.5} \tag{3}$$

Therefore, we arrive at TFP in Equation (4):

$$TFP_{it} = EC_{it} * TC_{it} \tag{4}$$

The HDDS is a snapshot of a family's capacity to access a range of foods based on their financial situation (Kennedy et al., 2010; Headey and Ecker, 2013). It has previously been employed as a proxy for food access in the home as part of the Food and Nutrition Technical Assistance Project (FANTA) (Swindale and Bilinsky, 2006). The score was calculated by aggregating the number of days that households consumed at least one item from each of the 12 specified food groups in the previous 7 days (Sibhatu et al., 2015). The range of the HDDS is from 0 to 12.

The HDDS is written as follows:

$$HDDS\left(0-12\right) = \sum\left(A + B + C + D + E + F + G + \mathrm{H} + I + J + K + L\right)$$

The HDDS indicator is calculated over a 7-day recall period using 12 food groups: cereals; pulses; fruits, vegetables; edible oil; meat, eggs, and milk; fruits; large fish; small fish; spices; drinks and beverages; and other foods produced outside the home. The values for A to L can be 0 or 1.

The HWI is a composite variable created using principal component analysis (PCA). Variables for household land, assets, and productive assets, as well as home amenity ownership indicators, were included in the PCA model. Among the vital commodities are a car, motorcycle, bicycle, radio, gas cooker, sewing machine, bed, and cell phone, as well as livestock (Mutisya et al., 2016). Formally, the HWI for household i is the following linear combination in Equation (5):

$$Y_i = \alpha_i\left(\frac{X_1 - \overline{X_1}}{S_i}\right) + \alpha_2\left(\frac{X_2 - \overline{X_2}}{S_2}\right) + \ldots + \alpha_k\left(\frac{X_k - \overline{X_k}}{S_k}\right) \tag{5}$$

where $\overline{X_k}$ and S_k are the mean and standard deviation of asset X_k, respectively, and α represents the weight for each variable X_k for the first principal component. X_k are the household current assets, household-level productive assets, and livestock value.

The farmers' LVI is a composite variable. The integrated indicators approach established by Hahn et al. (2009) was used to measure it. Based on previous research (Hahn et al., 2009; Gerlitz et al., 2017; Adu et al., 2018; Amuzu and Kabo-bah, 2018; Parker et al., 2019), the LVI was derived from five major components, including social capital (group membership, access to NGOs, access to banks, access to agricultural offices, access to input dealers, etc.), human capital (education, age, information, access to information), physical capital (household assets, household agricultural productive aspects, mobile access, access to water), financial capital (savings, loans, value of livestock, ownership of plot), and natural capital (access to water supply, amount of land, etc.). Several observations are included in each major component, with each sub-value component being determined on a distinct scale. Each sub-value component was standardized into an index (Hahn et al., 2009) as follows in Equation (6):

$$Index_{sr} = \frac{S_r - S_{\min}}{S_{\max} - S_{\min}} \tag{6}$$

Here, the mean value of the sub-component indicators is S_r, whereas the minimum and maximum values are $S_{\min}$ and $S_{\max}$, respectively. To obtain the index of each major component, the sub-component indicators were averaged as follows in Equation (7):

$$M_r = \frac{\sum_{i=1}^{n} index_{S_{ri}}}{n} \tag{7}$$

where: M_r is one of the five major components for region r (social capital, human capital, physical capital, financial capital, and natural capital); S_{ri} denotes the sub-components that make up each major component, which are indexed by i; and n is the number of sub-components in each major component. Once the values for each of the five major components for a region are calculated, they are averaged using Equation (8) to obtain the region-level LVI:

$$LVI_r = \frac{\sum_{i=1}^{n} W_{Mi} M_{ri}}{\sum_{i=1}^{7} W_{Mi}} \tag{8}$$

where: LVI_r denotes the mean value of the livelihood vulnerability index; M_{ri} denotes the value of one of the major components i; and W_{Mi} denotes the weights of each major component i.

It is worth noting that Equation (8) can be expanded as follows through Equation (9):

$$LVI_r = \frac{W_{SDP} SDP_r + W_{LS} LS_r + W_H H_r + W_{SN} SN_r + W_F F_r + W_W W_r + W_{NDC} NDCV_r}{W_{SDP} + W_{LS} + W_H + W_{SN} + W_F + W_W + W_{NDC}} \tag{9}$$

The WEAI was used to assess women's empowerment. The WEAI, launched in March 2012 by the Oxford Poverty and Human Development Initiative (OPHI), the United States Agency for International Development (USAID), and the IFPRI, is a direct indication of economic empowerment and gender parity at the household and individual levels (Yang and Stanley, 2012; Alkire et al., 2013). The multidimensional empowerment measurement, using the Alkire–Foster method, helps to illustrate women's accomplishments in 10 indicators and five empowerment areas (5DE). The opposite of empowerment in these five areas is de-empowerment, which is computed as follows using Equation (10):

$$5DE = 1 - M_o \tag{10}$$

where M_o is the overall disempowerment score, while $5DE$ is measured using 10 indicators with their respective weights. Each sign indicates whether or not a person is meeting their goals in that area.

Another unique component of the WEAI is the gender parity index (GPI), which compares women's and men's empowerment across the 5DE in the same household. It can be expressed as follows:

$$WEAI = 0.90(5DE) + 0.10(GPI) \tag{11}$$

where: $5DE$ is the degree of empowered women; and GPI is the relative empowerment of women in the household, according to the WEAI for gender empowerment in agriculture. The weights assigned to the index are 0.9 for $5DE$ and 0.1 for GPI.

Multivariate multiple regression model

We estimated the impact of TFP on HDDS and LVI using a standard multivariate linear regression model. The functional form of a multivariate regression model is given below in Equation (12):

$$Y_{n\times m} = f\left(x_{n\times(r+1)}, \beta^0_{(r+1)\times m}\right) + \varepsilon_{n\times m} \tag{12}$$

$$\text{where } Y_{n\times m} = \begin{bmatrix} Y_{11} & Y_{12} \cdots & Y_{1m} \\ Y_{21} & Y_{22} \cdots & Y_{2m} \\ \cdots & \cdots \cdots & \cdots \\ Y_{n1} & Y_{n2} \cdots & Y_{nm} \end{bmatrix}, \varepsilon_{n\times m} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} \cdots & \varepsilon_{1m} \\ \varepsilon_{21} & \varepsilon_{22} \cdots & \varepsilon_{2m} \\ \cdots & \cdots \cdots & \cdots \\ \varepsilon_{n1} & \varepsilon_{n2} \cdots & \varepsilon_{nm} \end{bmatrix},$$
$$n = 1,\ldots,N \text{ and } m = 1,\ldots,M$$

$$\beta^0_{(r+1)\times m} = \begin{bmatrix} \beta_{01} & \beta_{02} \cdots & \beta_{0m} \\ \beta_{11} & \beta_{12} \cdots & \beta_{1m} \\ \cdots & \cdots \cdots & \cdots \\ \beta_{r1} & \beta_{r2} \cdots & \beta_{rm} \end{bmatrix},$$
$$\Sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} \cdots & \sigma_{1m} \\ \sigma_{21} & \sigma_{22} \cdots & \sigma_{2m} \\ \cdots & \cdots \cdots & \cdots \\ \sigma_{n1} & \sigma_{n2} \cdots & \sigma_{nm} \end{bmatrix} \text{ and } E\left(\varepsilon_{(i)}\right) = 0$$

where: $Y_{n\times m}$ is a 1×2 vector of the response variables HDDS and LVI; and $x_{n\times(r+1)}$ is a 2×8 matrix of the predictor variables listed in Table 1.

4 Results

4.1 Measuring the TFP of rice farming households

Enhancing rice production efficiency so that maximum output can be produced with the same number of inputs is crucial for improving food security. To evaluate this, the efficiency of the TFP is utilized. This is a measure of how well agricultural land, labor, capital, and materials are used to generate an agricultural output, and the ratio of total agricultural output to total production inputs is used to calculate it.

When more output is produced from a fixed number of resources, TFP increases, indicating that resources are being used more efficiently (IFPRI, 2018). This contributes to the sustainable development of livelihoods, which leads to increased food and nutrition security. Household food security is far more difficult to achieve, as it is influenced by agricultural production factors and numerous sources of income and wealth that influence food purchases, as well as other services, such as nutrition education, health, water, and sanitation (Ragasa and Mazunda, 2018). TE, EC, TC, and TFP were estimated using a stochastic frontier model. The results revealed technical efficiencies of 0.637 and 0.646 in 2015 and 2018, respectively. This indicates that rice farmers have opportunities to increase TE by 35% to increase production with the same amount of inputs. The overall economic efficiency was 1.29%, while TFP was only 70% (see Table 2).

TABLE 2 The TFP of rice farming households.

Parameters	Value
Technical efficiency in 2015 (TE_{15})	0.637
Technical efficiency in 2018 (TE_{18})	0.646
Economic efficiency: $EC_{it} = \frac{TE_{18}}{TE_{15}}$	1.287
Technical change: $TC_{it} = (TE_{18} \times TE_{15})^{\frac{1}{2}}$	0.627
Total factor productivity: $TFP_{it} = EC_{it} \times TC_{it}$	0.703

Economic efficiency, which is a measure of the ratio between technical efficiencies in different years, was calculated to be 1.287, indicating the overall efficiency of production processes. The technical change factor, showing the combined impact of technical efficiencies, was found to be 0.627. The TFP was determined to be 0.703, signifying the level of productivity achieved by rice farming households in Bangladesh. This value reflects the efficiency of utilizing resources such as land, labor, capital, and materials to generate agricultural output. A higher TFP indicates a more efficient use of resources, leading to increased agricultural productivity and potentially improved food security and livelihood outcomes for farmers.

Figure 2A shows the distribution of TE scores. The rice farmers' TE scores ranged from 0 to 1, with a higher number indicating better production techniques. The farmers' average TE was 0.63, implying that they could lower their input use by 37% while maintaining the same output level if they produced rice at the same level as the best farmers. The distribution of TE scores (Figure 2A) shows that most rice farms (almost half) had TE values between 0.61 and 0.80. Figure 2B depicts the TFP of rice farming households. The results reveal that, for the last 3 years studied (from 2015 to 2018), the average value of TFP was 0.702, which demonstrates an increase in the TFP. If farmers produced rice in the same manner as the most efficient farmers, they could lower their input use by 29% while maintaining the same level of production. The largest concentration (approximately 40.85%) of TFP scores was between 0.81 and 5.43.

4.2 Dietary status of households

The HDDS is a food security assessment tool that has been validated in a number of countries as an approximate estimate of food availability and accessibility, which are two crucial factors of food security (Yohannes et al., 2002; Swindale and Bilinsky, 2006; WFP, 2009; Cordero-Ahiman et al., 2017). It determines how much of each food was consumed at home in a specific time period, such as the last 24 or 48 h (Teklewold et al., 2013; Cordero-Ahiman et al., 2017). The HDDS is a continuous score ranging from 0 to 12, with higher scores indicating higher nutrient intake based on whether the household consumes each of the 12 food groups previously detailed. Table 3 shows the results for the household dietary status of the farm households.

Dietary variety was low in 0.11% of the homes, according to the findings (with a HDDS of less than 6). With scores ranging from 7 to 9 points, 16.24% of families fall into the medium dietary variety category, while the remaining 83.65% fall into the higher dietary diversity category, with scores exceeding 10 points. This means that 16.35% of households lack adequate dietary diversification, whereas the majority (83.65%) have adequate dietary diversification.

Hahn et al. (2009) created the LVI to quantify farmers' vulnerability to climate change and unpredictability (Adu et al., 2018). This vulnerability is measured by the LVI value, which ranges from 0 to 1. The higher the LVI number, the greater the vulnerability. We found that the sample rice farmers are moderately vulnerable to climate change, as measured by the LVI index value of 0.454. The weighted average of inputs, labor, and capital was used to compute TFP, which is a measure of productivity calculated by dividing the total output of the entire economy by the weighted average of inputs, labor, and capital. This denotes whether the actual output growth is outpacing the increase in inputs such as manpower and capital. We found the average TFP to be 0.702.

The descriptive statistics for the HDDS, LVI, and TFP are shown in Table 4.

4.3 Pearson's correlation

Pearson's correlation coefficient results show that the HDDS and LVI are significantly correlated ($p < 0.01$) (Table 5). There is a weak positive correlation between the LVI and HDDS ($r = 0.1004$; $p < 0.01$) but a strong positive correlation between Hsize and the HDDS ($r = 0.208$; $p < 0.01$). TFP has a positive correlation with the WEAI ($r = 0.037$; $p < 0.109$) and the HWI ($r = 0.012$; $p < 0.582$) but a negative correlation with PCFEP ($r = -0.013$; $p < 0.10$) and HWF ($r = -0.038$; $p < 0.570$). The LVI is weakly positively correlated with Hsize ($r = 0.166$; $p < 0.01$) and the HWI ($r = 0.029$; $p < 0.10$). The HDDS is weakly positively correlated with TFP ($r = 0.018$; $p < 0.10$), Hsize ($r = 0.208$; $p < 0.01$), the WEAI ($r = 0.061$; $p < 0.01$), PCFEP ($r = 0.176$; $p < 0.01$), HWF ($r = 0.124$; $p < 0.01$), and the HWI ($r = 0.072$; $p < 0.01$).

Table 5 provides correlation coefficients for TFP with HDDS and LVI. The study found a positive correlation between TFP and HDDS, indicating that as TFP increases, the HDDS also tends to increase. On the other hand, there was a negative correlation between TFP and LVI, suggesting that higher TFP can lead to lower livelihood vulnerability.

Causal relationships among the key variables

Causal relationships between key variables may consist of direct and indirect effects. Direct causal effects are effects that go directly

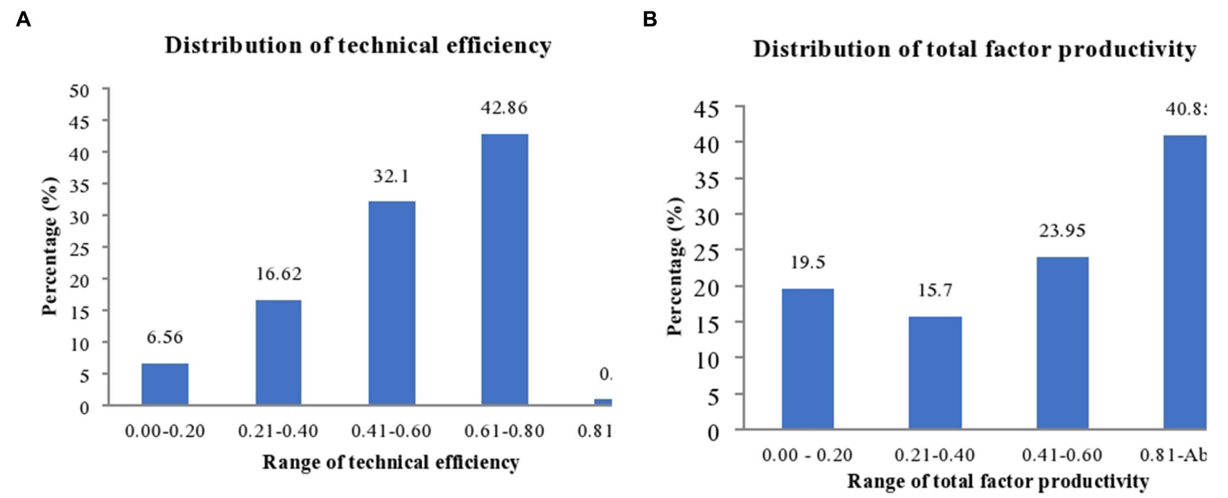

FIGURE 2
(A) Technical efficiency (TE) distributions of rice farmers. **(B)** Total factor productivity (TFP) distributions of rice farmers.

TABLE 3 Categorization of respondents with respect to the HDDS.

HDDS category	Cut-off value	Frequency	Percent
Low	0–6	2	0.11
Medium	7–9	299	16.24
High	10–12	1,540	83.65

TABLE 4 Descriptive statistics for the HDDS, LVI, and TFP.

Variable	Average	St. dev.	St. err.
HDDS	10.72	1.201	0.028
LVI	0.454	0.059	0.001
TFP	0.702	0.352	0.008

from one variable to another. Indirect effects occur when one or more variables mediate the relationship between two variables. Path diagrams can be used to visualize the structural equation model: Figure 3 shows that the variables (TFP, LVI, and HDDS) are interconnected. We find that TFP has a direct positive effect on the HDDS but has a negative effect on the LVI.

The diagram illustrates how TFP significantly negatively influences the Livelihood Vulnerability Index (LVI), suggesting that increasing TFP can potentially reduce livelihood vulnerability among rice farming households in Bangladesh. Additionally, the diagram highlights a positive dependence of HDDS on TFP and LVI, indicating that higher TFP can lead to improved household dietary diversity, which is essential for better nutrient intake and overall food security status.

Table 6 presents the total causal effect. We found a significantly inverse relationship between the LVI and TFP ($\beta = -0.007$; $p < 0.05$) but a positive relationship between the HDDS and TFP.

4.4 Regression results

Our regression results are presented in Table 7, which highlights the impact of TFP on the HDDS and LVI. Notably, we see that TFP has a significant positive effect on the HDDS, implying a one-unit increase in TFP, on average, increases the HDDS by 0.127 units. In addition, the WEAI also has a significantly positive effect on the HDDS. Table 6 also reveals that higher scores for the HWI, Hsize, PCFEP, and HWF are all associated with a higher HDDS levels.

The HDDS is an important nutrition outcome measuring the economic ability of a household to access a variety of foods (Huluka and Wondimagegnhu, 2019). Our results are in line with our *a priori* assumptions and highlight the fact that PCFEP is a key indicator of a household's ability to buy enough staple and nutritious food. Our results show that PCFEP has a significant positive impact on the HDDS. We argue that the positive effects of Hsize on the HDDS may be attributed to the fact that large families typically have more non-farm income and a greater ability to purchase diversified food items. This result is in contrast to some prior studies that have found that Hsize has a negative impact on HDDS (Adesina and Zinnah, 1993; Mulmi et al., 2017; Ochieng et al., 2017).

Similarly, our finding that HWF has a positive impact on the HDDS makes intuitive sense, as it is a good proxy of household welfare, as confirmed by Chegini et al. (2021). Government social safety net programs represent one of the strategies to improve households' food consumption. Hailu and Amare (2022) found that an effective safety net program significantly increases households' calorie intake. In the present study, we found that ASSNT has a negative relationship with the HDDS, which means that the farm households receiving safety net support invest monies in non-food expenditure for income-generating activities.

Our results also clearly show that TFP significantly lowers the level of the LVI, with a one-unit increase in TFP decreasing the LVI by 0.007 units. Interestingly, the LVI is positively affected by Hsize, PCFEP, having a farming household, and ASSNT. Again, these results appear to be intuitively reasonable. Large households are better able to diversify their talents and, generate non-farm income when needed and lower their livelihood vulnerability levels. The LVI is used to measure the vulnerability of farm households to climate change and variability. Furthermore, the more households spend on food *per capita*, the lower their LVI. There is also obviously a direct relationship between ASSNT and a lower LVI. In addition, we found that PCFEP has a significant positive impact on farmers' LVI. The

TABLE 5 Pearson's correlation coefficient between the continuous variables.

	HDDS	LVI	TFP	Hsize	WEAI	PCFEP	HWF	HWI
HDDS	1							
LVI	0.1004***	1						
	(0.000)							
TFP	0.018	−0.0437*	1					
	(0.424)	(0.061)						
Hsize	0.208***	0.166***	−0.024	1				
	(0.000)	(0.000)	(0.302)					
WEAI	0.061***	−0.027	0.037	−0.088***	1			
	(0.008)	(0.247)	0.109	(0.000)				
PCFEP	0.176***	−0.028	−0.038*	−0.398***	0.008	1		
	(0.000)	(0.224)	(0.096)	(0.000)	(0.715)			
HWF	0.124***	−0.005	−0.013	0.169***	−0.061***	0.005	1	
	(0.000)	(0.817)	(0.570)	(0.000)	(0.008)	(0.799)		
HWI	0.072***	0.029	0.012	0.109***	0.031	−0.039*	0.09***	1
	(0.001)	(0.204)	(0.582)	(0.000)	(0.181)	(0.089)	(0.000)	

HDDS, Household dietary diversity score; LVI, Livelihood vulnerability index; TFP, Total factor productivity; HWI, Household wealth index; HWF, Household welfare (yearly non-food expenditure); PCFEP, Per capita food expenditure; WEAI, Women's empowerment in agriculture index; Hsize, Household size. *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

coefficient for the Total Factor Productivity (TFP) variable is 0.1269, with a standard error of 0.0739. The *t* value for this coefficient is 1.720, and the *p* value is 0.0860. The results showed that TFP had a significant impact on both HDDS and LVI, underlining the importance of TFP in improving food security and reducing livelihood vulnerability.

Government safety nets have a clear and measurable impact on the lives of low-income families and reduce their food insecurity. Many safety net programs have been launched in the study area, such as old age allowance, widow allowance, vulnerable group development (VGD)/vulnerable group feeding (VGF), test relief, food for work, cash transfers, food transfers, price subsidies, job generation, housing for the homeless, an efficiency development fund for expatriate workers, *Ekti Bari Ekti Khamar*, and microcredit, among many others. We found that ASSNT has a positively significant ($p < 0.01$) association with the LVI. When rice farmers are exposed to the adverse impacts of natural hazards, injury, loss, or disruption to their livelihood, safety nets play a crucial role in protecting them.

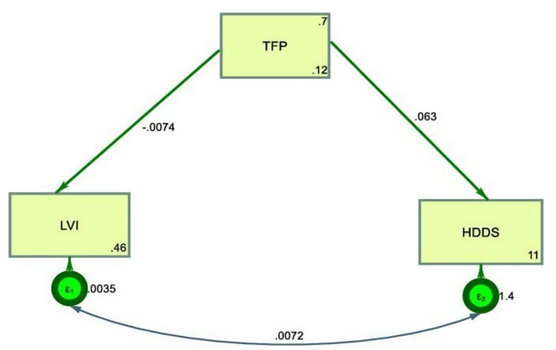

FIGURE 3
Path diagram of structural equation model.

5 Discussion

This manuscript examines the relationship between TFP, LVI, and HDDS in rice farming households in Bangladesh. The study analyzes data from the Bangladesh Integrated Household Survey 2015 and 2018 using econometric methods such as the stochastic frontier model, multivariate regression analysis, and structural equation modeling. The results show that TFP significantly affects both LVI and HDDS. Higher TFP is associated with reduced LVI and increased HDDS among rice farming households, similar to previous studies (Alam et al., 2011, 2014; Hoq et al., 2021). This suggests that improving TFP can enhance food security and reduce vulnerability in these households. The multivariate regression analysis reveals that TFP, household wealth index, women's empowerment in agriculture index, *per capita* food expenditure, household level welfare, and household size have a positive impact on HDDS, while TFP is negatively associated with LVI, along with *per capita* food expenditure and household size (Dua and Garg, 2019). The study also examines the correlation between TFP, HDDS, and LVI using Pearson's correlation coefficients and structural equation modeling. The multivariate regression model used in the study identifies significant indicators related to HDDS and LVI, as well as the impact of TFP on these measures. Overall, the findings suggest that increasing TFP is crucial for improving food security (Saha et al., 2021), reducing livelihood vulnerability, and achieving sustainable development goals in countries like Bangladesh. Higher TFP leads to positive outcomes in terms of household dietary diversity and livelihood vulnerability, underscoring the importance of advancing agricultural policies to enhance TFP in order to achieve food security and reduce vulnerability in rice farming households. The study's findings could be valuable for policymakers and professionals in formulating advanced agricultural

TABLE 6 Total effect.

	Coefficient	OIM std. err.	z	$Pr > z$	95% conf. interval	
LVI → TFP	−0.007	0.003	−1.870	0.061	−0.015	0.000
HDDS → TFP	0.063	0.079	0.800	0.425	−0.092	0.219

TABLE 7 Multivariate regression results.

Variable	Obs.	Parms	RMSE	R^2	F	p
HDDS	1,840	9	1.115	0.1406	37.444	0.000
LVI	1,840	9	0.058	0.0455	10.900	0.000
	Coefficient	Std. err.	t	$Pr > t$	95% conf. interval	
HDDS						
TFP	0.127*	0.073	1.72	0.086	−0.018	0.272
Hsize	0.221***	0.016	13.30	0.000	0.188	0.253
WEAI	0.834***	0.205	4.06	0.000	0.431	1.238
PCFEP	0.001***	0.000	12.61	0.000	0.000	0.000
HWF	0.001***	0.000	2.95	0.003	0.000	0.000
Occup	−0.066	0.054	−1.21	0.227	−0.172	0.041
HWI	0.039*	0.023	1.71	0.087	−0.006	0.085
ASSNT	−0.10*	0.053	−1.86	0.064	−0.206	0.006
Constants	8.561***	0.196	43.52	0.000	8.175	8.945
LVI						
TFP	−0.007*	0.003	−1.84	0.066	−0.015	0.001
Hsize	0.006***	0.001	6.85	0.000	0.004	0.008
WEAI	−0.005	0.011	−0.46	0.643	−0.026	0.016
PCFEP	0.000**	0.000	2.36	0.018	0.000	0.000
HWF	0.000	0.000	−1.33	0.185	0.000	0.000
Occup	0.011***	0.003	3.80	0.000	0.005	0.016
HWI	0.001	0.001	0.70	0.481	−0.002	0.003
ASSNT	0.009***	0.003	3.19	0.001	0.004	0.015
Constants	0.422***	0.010	41.01	0.000	0.402	0.442

*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

policies to achieve food security and reduce livelihood vulnerability in the country.

6 Conclusion

The study on TFP and its impact on food security and livelihood vulnerability of rice farming households in Bangladesh offers valuable insights for policymakers and professionals in the agricultural sector. The investigation utilized a multivariate modeling approach and data from the Bangladesh Integrated Household Survey to analyze the relationship between TFP, HDDS, and LVI. The findings indicate that increasing TFP can reduce livelihood vulnerability and improve food security, contributing to sustainable development Goal 2. The study identified significant indicators related to household dietary diversity score and livelihood vulnerability index, highlighting the importance of TFP in influencing these measures. Specifically, TFP was found to have a positive association with household dietary diversity score and a negative association with livelihood vulnerability index, underscoring its crucial role in enhancing food security and reducing livelihood vulnerability. The study suggests that policymakers and professionals should prioritize implementing advanced agricultural policies that focus on increasing TFP to achieve food security and mitigate livelihood vulnerability in developing countries like Bangladesh. Recommendations may include enhancing access to technology-related services, closing gaps in women's empowerment and technical efficiency, and promoting agricultural input intensification. However, the study is limited in its generalizability as it specifically focused on rice farming households in Bangladesh. Further research is needed to explore the intricacies of the relationship between TFP, food security, and livelihood vulnerability in more depth, possibly considering additional factors or variables that could influence these outcomes. Overall, the study provides a solid foundation for understanding the importance of TFP in improving food security and reducing LVI. It offers valuable insights for policymakers and professionals to guide future agricultural policies and interventions in Bangladesh and beyond.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: https://www.ifpri.org/publication/bangladesh-integrated-household-survey-bihs-2018-2019.

Author contributions

PS: Writing – original draft, Software, Formal Analysis, Data curation, Conceptualization. MA: Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. IB: Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. AM: Writing – review & editing, Validation, Methodology, Conceptualization.

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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.

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Qiang Xu,
Yangzhou University, China

*CORRESPONDENCE
Renée P. M. Cardinaals
✉ renee.cardinaals@wur.nl

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The complementarity of nutrient density and disease burden for Nutritional Life Cycle Assessment

Renée P. M. Cardinaals[1]*, E. Verly Jr[2], O. Jolliet[3], H. H. E. Van Zanten[1,4] and T. Huppertz[5,6]

[1]Farming Systems Ecology Group, Department of Plant Sciences, Wageningen University and Research, Wageningen, Netherlands, [2]Department of Epidemiology, Institute of Social Medicine, Rio de Janeiro State University, Rio de Janeiro, Brazil, [3]Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University Denmark, Kgs Lyngby, Denmark, [4]Department of Global Development, Cornell University, Ithaca, NY, United States, [5]Food Quality and Design Group, Wageningen University and Research, Wageningen, Netherlands, [6]Friesland Campina, Amersfoort, Netherlands

The triple burden of obesity, undernutrition and climate change calls for systemic action to find solutions that co-benefit human and planetary health. A Nutritional Life Cycle Assessment (nLCA) can be used as a tool to assess the health- and environmental impact of foods and guide a transition to healthy and sustainable diets. Thus far, nLCAs have used the nutrient content of foods to represent their health impact, whereas the disease risk linked to under- or overconsuming certain nutrients, foods or food groups has been largely underutilized. This study explored, for the Dutch diet, the correlation between an indicator for essential nutrient density and for the disease burden of individual food items, i.e., a Nutrient Rich Food index with 24 essential nutrients (NRF24) and the HEalth Nutritional Index (HENI), respectively. NRF24 and HENI scores were calculated for food items contained in the Dutch Food Composition database. A very weak correlation between NRF24 and HENI values confirmed that nutrient density and disease burden should be considered as complementary and thus, that a high nutrient density does not directly imply a low disease burden, and vice versa. Moreover, the direction and strength of the correlation was food group-dependent, with negative correlations between NRF24 and HENI mainly observed for animal-based products, with the exception of dairy. In addition, the correlations between the nutrition-based indicators and indicators for greenhouse gas emissions, land use and water use were mostly weak, which stresses the need to include health impact in traditional LCAs because foods with a high nutrient density and low disease burden can imply trade-offs due to high environmental impacts. We therefore conclude that multiple indicators for health and environmental impact should be considered side-by-side in nLCA to avoid the risk of missing important information and trade-offs when assessing the performance of individual food items for healthy and sustainable diets.

KEYWORDS

nutrition, planetary health, life cycle assessment, healthy and sustainable diets, diet-related diseases, nutrient density

1 Introduction

Obesity, undernutrition and climate change are today's largest threats to human health (Swinburn et al., 2019). Despite attempts, malnutrition continues to increase: trends in obesity, child stunting and wasting, deficiencies in essential micronutrients and maternal anemia are all issues of concern (FAO, IFAD, UNICEF, WFP, and WHO, 2022). Moreover, today's food systems generate a large share of human-induced environmental impacts, such as greenhouse gas emissions, land use change, acidification, eutrophication and biodiversity loss (Poore and Nemecek, 2018). This "Global Syndemic" calls for systemic action to find solutions that co-benefit human health and planetary health (Swinburn et al., 2019; Branca et al., 2020). In this regard, adopting diets that are simultaneously beneficial for human and planetary health – i.e., healthy and sustainable diets – can be an effective lever of change (Tilman and Clark, 2014; Drewnowski et al., 2020). Such a dietary shift, however, requires the identification of food items that are in line with the desired outcome. If done correctly, such information on food item level can serve as scientific basis for food labeling or food-based dietary guidelines (Bunge et al., 2021).

To identify food items that fit in diets that benefit both human and planetary health, a methodological approach is required that can quantify associated impacts (Green et al., 2020). For environmental impacts of goods and services, Life Cycle Assessment (LCA) is regarded as the principal tool (Thoma et al., 2022). LCA studies can be performed at the food item level to compare or identify products for environment-friendly diets. However, LCA studies generally do not fully consider the primary function of food: to sustain and promote human health via the supply of nutrients and other compounds. This was addressed by the introduction of the nutritional LCA (nLCA) (McLaren et al., 2021). However, there is no consensus about which aspects should be considered and how the function(s) of food should be integrated in an nLCA (McAuliffe et al., 2020; McLaren et al., 2021). For example, an nLCA may use a complementary functional unit that reflects the nutrient content of a food item (Drewnowski et al., 2015; Saarinen et al., 2017; Bianchi et al., 2020). This, however, could favor food items with a high environmental impact relative to a high contribution to daily nutrient requirements. Nutrient profiling systems such as the Nutrient Rich Food (NRF) index, which is commonly referred to as nutrient density, have been used to serve as complementary functional unit in nLCA (Bianchi et al., 2020). However, nutrient profiling systems are subject to several methodological choices that can influence the interpretation of the LCA result (Hallström et al., 2018) as they implicitly weigh the different considered nutrient contributions to recommended daily doses equally irrespective of the magnitude of their health impacts and therefore their application as functional units in nLCA has been debated (McLaren et al., 2021).

Moreover, nutrients are not the only aspect of food that directly affects human health. The consumption of certain foods may also increase or decrease the risks for non-communicable diseases (NCDs) (Afshin et al., 2019). NCDs are chronic diseases that arise from a combination of genetic, physiological, environmental and behavioral risk factors (e.g., cardiovascular diseases, cancers, chronic respiratory diseases and obesity) and are the number one cause of death worldwide. Although highly relevant for human health, very few studies have assessed the direct link between foods and NCDs as an indicator in nLCA (Weidema and Stylianou, 2020). Studies in the United States and Europe have used epidemiologically-based relative risks determined by the Global Burden of Disease (GBD) study for 15 different beneficial and detrimental risk factors (nutrients and food groups) to determine the associated marginal health impacts and to include this as an additional Life Cycle Impact category covering nutritional health impacts (Ernstoff et al., 2020; Stylianou et al., 2021). These studies determined the Disability Adjusted Life Years (DALYs) associated with the food composition in the GBD risk components, but so far they do not cover health impacts that may be related to inadequate nutrient intake for nutrients such as zinc, iron or vitamin A, that are covered separately in the GBD. Other essential nutrients, like vitamin B12, are also not covered. Suggesting the need for combining nutrient based and disease-based approaches. To that regard, some study results suggest that nutrient dense foods will inherently reduce the risk for NCDs (Hoeft et al., 2012; Bruins et al., 2019) but the actual relationship between nutrient density and disease-based indicators on a food item level has not yet been studied. That is, indicators for nutrient density and disease burden have been applied in nLCA independently but this fails to address their possible complementarity (Guo et al., 2022). In the case of some food items, this complementarity may be relevant as a high nutrient density does not rule out other dietary risks, e.g., red meat (Givens, 2018). Moreover, on a dietary level no significant correlation between nutrient density and disease burden has been found, with some diets being nutritionally adequate but linked to high DALYs and other diets being linked to low DALYs but lacking several nutrients (Chen et al., 2019).

In addition to the lack of addressing the relation between nutrient density and disease burden, previous work has shown that trade-offs exist between nutritional and environmental impacts on food item level (Drewnowski et al., 2015; Stylianou et al., 2021). This suggests that there are multiple dimensions that do not correlate and should be considered in nLCA to avoid missing relevant information or make decisions that lead to unforeseen trade-offs or rebound effects. The aim of this study is to gain insight in how indicators for nutrient density and disease burden relate each other, as well as to environmental impacts, and explore how they can be included in nLCA to ultimately make better informed decisions for healthy and sustainable food choices, e.g., through food labelling (Bunge et al., 2021).

2 Materials and methods

Nutrition-based indicators were calculated for 1826 food items in the Dutch Food Composition database, i.e., Nederlands Voedingsstoffenbestand (V7.0) (RIVM, 2021). This database provides nutrient content data on 130 macro- and micronutrients for2207 food items. The following food groups were excluded from the analysis: "alcoholic drinks," "mixed dishes," "infant foods," "herbs and spices" and "miscellaneous." All non-alcoholic beverages that were either "light" or contained zero calories were also excluded as they may heavily skew the data when scores are calculated on an energy basis.

Abbreviations: (μ)DALY, (micro) Disability Adjusted Life Years; DRF, Dietary Risk Factor; GBD, Global Burden of Disease; GWP, Global Warming Potential; HENI, HEalth and Nutritional Index; LU, Land use; NCD, Non-communicable disease; (n)LCA, (nutritional) Life Cycle Assessment; NRF, Nutrient Rich Food index; WU, Freshwater use.

In addition, all food items that lacked data for one or more nutrients required for calculations were omitted from the database. This resulted in a total of 1826 food items divided into 17 food groups (Supplementary Table 1). For these food items two nutrition-based indicators were calculated: a nutrient density score and a score for disease burden.

2.1 Nutrient density

An NRF24 was calculated based on the algorithm for the commonly used NRF9.3, which calculates the sum of the percentage of recommended daily intakes for nine food components to encourage (i.e., protein, fiber, vitamins A, C, and E, calcium, iron, magnesium, potassium), minus the sum of the percentage of RDAs for three nutrients to limit (i.e., sodium, saturated fat, added sugar) contained in 100 kcal of a food product (Fulgoni et al., 2009; Drewnowski, 2010). The algorithm of the NRF9.3 was adapted so that it only reflected the extent to which a food item can meet recommendations for essential nutrients, and excluded components that have an impact on health by increasing the risk for NCDs (fiber, saturated fat, sugar) (Supplementary Data 1.1). The resulting NRF24 covered 24 essential nutrients: protein, essential fatty acids (DHA, ALA and LA), sodium, potassium, calcium, phosphorous, magnesium, iron, copper, selenium, iodine, zinc, vitamins A, C, D, E, B1, B2, B3, B6, B9 and B12. These 24 nutrients covered all essential vitamins and minerals except for biotin, chloride, choline, chromium, fluoride, manganese, molybdenum and pantothenic acid. These eight nutrients were excluded as nutrient content data was lacking in the NEVO database. The NRF24 was calculated by default per 100 kcal of food item (Equation 1; Supplementary Figure 1).

$$\text{NRF24} = \left(\frac{\sum_{i=1}^{24} \left(\frac{EN_i}{DRI_i} \right)}{E * 100} \right) \quad (1)$$

Equation 1. Algorithm for NRF24 Where EN_i = Essential Nutrient i content per 100 g; DRI_i = Daily Recommended Intake for nutrient i; E = Energy content of food item (kcal/100 g).

Recommended daily intakes – or adequate intakes when the former were not available – for healthy adults from the Dutch Health Council were used (Health Council of the Netherlands, 2018) (Supplementary Table 2). No distinction was made in recommendations for men and women and an average was used when different for genders. For sodium, the adequate intake of 2000 mg/day as reported by EFSA and WHO was used (WHO, 2012; EFSA, 2023). We assumed no beneficial or unfavorable effects for a nutrient content higher than the recommended intake and therefore the scores were capped at 100% of this value.

2.2 Disease burden

The HEalth Nutritional Index (HENI) for a food item is a re-calculation of total Disability Adjusted Life Years (DALYs) due to the content of dietary risk components in the diet to the DALYs per gram of dietary risk component (Stylianou et al., 2021). DALYs represent the sum of years lost due to pre-mature mortality, to time lived in less than full health or to disability due to exposure to a risk factor, such as a dietary risk. Dietary risk components – i.e., calcium, fiber, omega-3 fatty acids from seafood, polyunsaturated fat, trans fatty acids, sodium, fruits, vegetables, milk, legumes, nuts and seeds, red meat, processed meat and whole grains – and the DALYs from insufficient or excess intake levels of these were obtained from the Global Burden of Disease (GBD) study (Afshin et al., 2019). The HENI for a food item indicates the minutes of healthy life lost or gained due to a marginal shift in the dietary risk component content of an adult's diet under the assumption that the health effect from multiple dietary risk components is independent and additive and that food components not covered by the GBD have neutral health effects. The calculation of HENI scores was similar to Stylianou et al. (2021), while updating the background data, using the latest GBD 2019 relative risks and using Dutch rather than US burden rates. This calculation required three steps: 1. Calculating the Dietary Risk Factors (DRFs) for the Dutch population, using Dutch specific burden rates for the considered diseases, 2. Determining the risk factor content of individual food items from the NEVO database and 3. Multiplying DRFs with risk factor content to calculate the HENI per food item. Calculating DRFs was done by creating a non-linear optimization to find the best dose–response curve for the GBD's 81 risk-outcome specific relative risks. This resulted in a change in risk per gram change in intake of a dietary risk component. Combining this with the observed burden rates, i.e., μDALYs per 100.000 individuals per year, in the Netherlands for each corresponding disease, resulted in DRFs (Supplementary Data 1.1; Supplementary Table 3). DRFs thereby reflected the amount of μDALYs lost or gained per gram of dietary risk component intake. For each of the 1826 food items the dietary risk component content was either calculated based on data extracted from the food composition data – i.e., for the dietary risks relating to intake of calcium, fiber, seafood omega-3 fatty acids, polyunsaturated fat, trans fatty acids and sodium – or based on the nature of the food item – i.e., for the dietary risks related to fruits, vegetables, milk, legumes, nuts and seeds, red meat, processed meat and whole grains. For composite food items, the dietary risk content was based on ingredient lists published on the website of the premium retailer in the Netherlands (Albert Heijn, 2023). To avoid double counting, the effects of calcium in milk, sodium in processed meat and fiber in fruit, vegetables and legumes, we excluded the diseases that were already considered in the DRFs of calcium, sodium and fiber from the diseases linked to milk, processed meat and fruit, vegetables and legumes, respectively. In the final step, DRFs were multiplied with each food item's dietary risk component content and a factor of −1 so that a positive HENI reflects minutes of healthy life gained and a negative HENI reflects minutes of healthy life lost per 100 kcal food item consumed (Equation 2; Supplementary Figure 1).

$$\text{HENI} = -0.53 * \left(\frac{\sum_{i=1}^{15} (DRFi * Ri)}{E * 100} \right) \quad (2)$$

Equation 2. Algorithm for HENI score where DRF=Dietary Risk Factor for i risk factor; R = dietary risk factor component per 100 g; E = energy content (kcal/100 g).

2.3 Environmental impact

LCA data for three environmental indicators – i.e., Global Warming Potential (GWP), land use (LU) and freshwater use (WU) – was publicly available for a subset of the initial food item dataset, providing LCA data for 200 food items (de Valk et al., 2016; RIVM, 2023). De Valk et al. (2016) selected food items based on their consumption frequency in the Netherlands (de Valk et al., 2016). The LCAs were performed using an attributional approach, followingISO14040 and ISO14044 guidelines. The system boundary was from cultivation to consumer, including end of life processes for food losses and packaging materials. Life Cycle Inventory data was taken from Agri-footprint and Ecoinvent V3, supplemented with in house data from Blonk consultants. For processes with multiple product flows, economic allocation was applied, with the exception for milk products for which physical allocation was applied (IDF, 2015). Inventory data for GWP, land use and freshwater use were translated into midpoint indicators using the LCIA impact model ReCiPe 2016 applying the hierarchical perspective (Huijbregts et al., 2017). GWP was calculated as the sum of CO_2 equivalents per kilogram of product for CO_2, CH_4 and N_2O emissions throughout the supply chain of a product. Land use was expressed as the number of square meters required per year for cultivation of food and animal feed and/or for raising livestock (including land transformation if applicable). Freshwater use was calculated as the amount of water consumed by producing 1 kg of product, expressed as m^3 per kg. Consumption includes evaporation, incorporation into the product, transfer to other watersheds or disposal into the sea, and is mainly driven by irrigation. For this study, GWP, land use and freshwater use were recalculated per 100 kcal of product. A detailed description of the LCA methodology applied to obtain the environmental indicator data used in this study can be found in Huijbregts et al. (2017).

2.4 Analysis of scores

The analyses were done using the scores of individual food items, food groups and animal-based versus plant-based food items. Food items that contained both animal- and plant-based ingredients were considered "mixed" and were excluded from the animal-based versus plant-based level comparison. All data processing and analyses were performed in RStudio 4.0. First, the correlation between NRF24 and HENI scores for all food items was calculated ($n = 1826$), and the correlations between NRF24 and HENI, and GWP, LU and WU for the LCA subset of food items were calculated ($n = 200$). The Spearman rank test was used for all correlations due to non-normality of the scores (Supplementary Figure 2; Supplementary Table 4). Secondly, to evaluate the performance of individual food items and apply this in an n-LCA, food items were categorized based on NRF24 and HENI scores (n = 200). Food items were considered "+/+" when NRF24 scores were ≥ 1.2, based on an optimal score of 24 for a 2000 kcal diet and a 1.2 equivalent for 100 kcal of food item (24 divided by 20), and HENI scores were ≥ 0. Food items were considered "−/−" when NRF24 < 1.2 and HENI <0 while "+/−" and "−/+" food items had an NRF24 ≥ 1.2 and HENI ≥0, and NRF24 < 1.2 and HENI<0, respectively. Thirdly, the categorization of food items in the environmental data subset was evaluated against environmental performance to identify food items that scored well on multiple indicators ($n = 200$).

2.5 Sensitivity analysis

Three sensitivity analyses were performed to test the effect of methodological choices on the results. First, we explored the impact of choosing a different reference unit. The correlations described in section 2.4 were therefore performed with NRF24 and HENI scores per 100 g and per serving size. Serving sizes were based on data from the National Institute for Public Health and the Environment (RIVM, 2020). Secondly, an NRF23 score was calculated by excluding sodium from the NRF24 and the correlation between NRF23 and NRF24 was calculated. This was done to assess the impact of excluding sodium as an essential nutrient from the NRF24. Excess sodium intake is not to encouraged for most of the population in developed countries and although capping was applied for individual food items in the main analysis, a combination of multiple high sodium food items into the diet may still result in excess sodium intake. Lastly, the NRF24 was replaced by the more commonly used NRF9.3, calculated as described previously and by Fulgoni et al. (2009) using Dutch recommended intakes (Supplementary Table 2). Nutrient content data could be extracted from the NEVO database, except for added sugars. Because data for added sugar is not included in the NEVO database, and it was not possible to make a distinction between added and natural sugars for each product, data for total sugars was used instead to calculate NRF9.3.

3 Results

3.1 Correlation between NRF24 and HENI

There was no clear association between NRF24 and HENI scores when assessing individual food items (Figure 1). NRF24 scores per 100 kcal ranged from 0.0 to 12.0, with the highest values observed for the food groups Fish and Vegetables and lowest scores for the food groups Sweets & Snacks, Cereal grains, and Condiments (Supplementary Table 5). HENI scores ranged from −38.8 to 50.5 minutes of healthy life lost per 100 kcal, with the highest scores observed for the food group Vegetables and the lowest scores for the food groups Red Meat and Processed Meat (Supplementary Table 5). The Spearman's rank test confirmed that there was no association between NRF24 and HENI scores with a weak correlation of $r = 0.21$, $p < 0.05$. (Supplementary Table 6). However, there was a clustering of food items in the same food group which suggests that food items within food groups have a similar relation between NRF24 and HENI (Figure 1). For the 17 food groups assessed, the correlations showed a large variation in strength and direction among the food groups which explains why the correlation between nutrient density and disease burden for all food items together was very weak (Figure 2; Supplementary Table 7). In general, plant-source products had a strong positive correlation between nutrient density and disease burden ($r = 0.62$, $p < 0.05$), especially fruits ($r = 0.63$), vegetables ($r = 0.62$), and tubers ($r = 0.53$), compared to all animal source products together ($r = -0.13$, $p < 0.05$) (Supplementary Figure 3). From the plant-source food

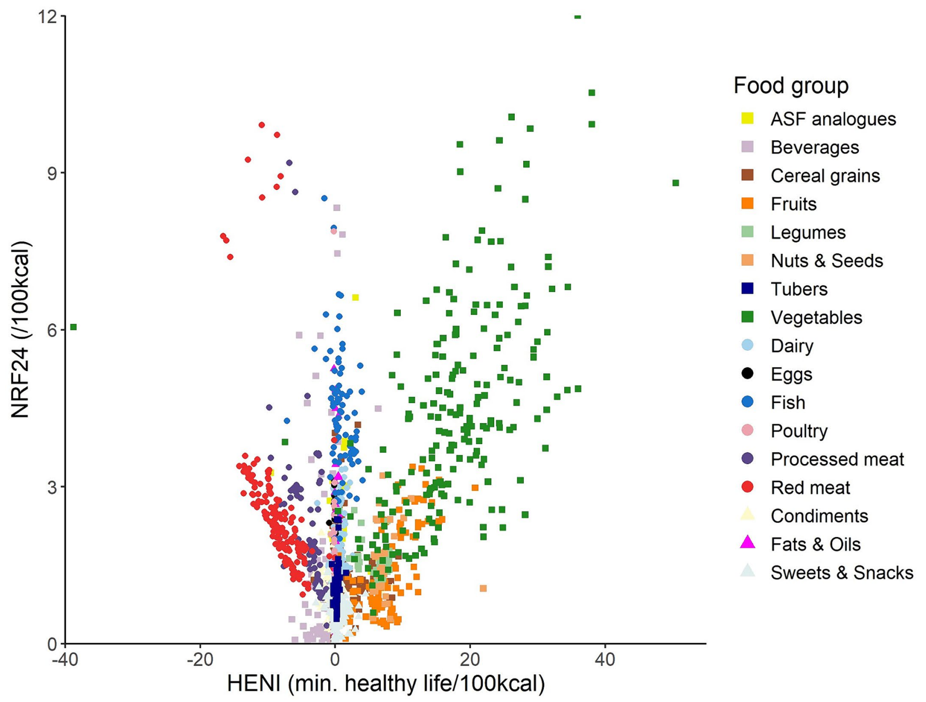

FIGURE 1
Correlation between NRF24 and HENI scores per 100 kcal for individual food items. Shapes: circles indicate animal-source food items, squares indicate plant-source food items, triangles indicate mixed-source food items.

groups, the correlations for nuts and seeds ($r = 0.16$) and legumes ($r = 0.12$) were not significant ($p > 0.05$). Correlations were negative for poultry, fish, processed meat, red meat, eggs and sweets and snacks. However, only for poultry, fish, processed meat and red meat the animal-based product groups, these negative correlations were significant ($p < 0.05$). These results show how some specific groups of animal products have a high nutrient density but increase the risk for disease burden while other food groups have a high nutrient density and decrease the risk for disease burden at the same time. In addition, Figure 2 shows that within food groups, there can be a large spread of scores, such as observed for legumes, eggs and dairy.

3.2 Correlation between NRF24 and HENI and environmental impacts

The correlation between NRF24 and HENI and environmental indicators differed widely but no strong correlations were found (Figure 3; Supplementary Table 5). The highest correlation existed between NRF24 and GWP ($r = 0.69$, $p < 0.05$), while the correlation for both LU and WU with NRF24 was less strong ($r = 0.37$ and 0.42, resp.; $p < 0.05$). There was no significant correlation for both GWP and LU with HENI ($p > 0.05$) and although statistically significant, HENI and WU were only weakly correlated ($r = 0.35$). In addition, the relation between HENI and GWP, as well as between HENI and LU, showed a U-shape with an inverse relation that suggests a reduction in environmental impact with an increase in HENI score for the left side of the plot while the right side of the plot suggests that an increase in HENI is related to a higher environmental impact.

3.3 Sensitivity analysis

The sensitivity analysis showed that correlations on food group level are different when scores are calculated with mass or serving as reference unit (Supplementary Table 7). The largest changes were observed for food groups containing foods with either a high nutrient density and high energy content (correlations increased) or a low nutrient density and low energy content (correlations decreased). Applying capping in the NRF24 calculation resulted in relatively lower scores than expected when scores were calculated per 100 grams or serving, which ultimately changed the correlation with HENI scores where no capping was applied. Nevertheless, the overall correlation between NRF24 and HENI remains weak with $r = -0.16$ ($p > 0.05$) and $r = 0.00$ ($p > 0.05$) for scores calculated per 100 grams and per serving, respectively (Supplementary Table 5; Supplementary Figure 4). This indicates that using an alternative reference unit does not change the absence of an association between nutrient density and disease burden.

The correlation between NRF23 (excluding sodium) and NRF24 confirmed little effect from including sodium as an essential nutrient ($r = 0.99$, $p < 0.05$). This indicates that it suffices to include the detrimental health effect of excess sodium intake as a dietary risk factor component in the HENI score, and that including it as an essential nutrient in the NRF24 does not skew the results.

The correlation between NRF9.3 and HENI increased compared to NRF24 and HENI ($r = 0.20$ to $r = 0.38$) which can be explained by the overlap between the scores, i.e., sodium and fiber are covered by both indicators while added sugar in NRF9.3 is covered to a certain extent by sugar sweetened beverages in the HENI score. Stronger correlations were also found for most food groups (Supplementary Table 8; Supplementary Figure 6). However, the

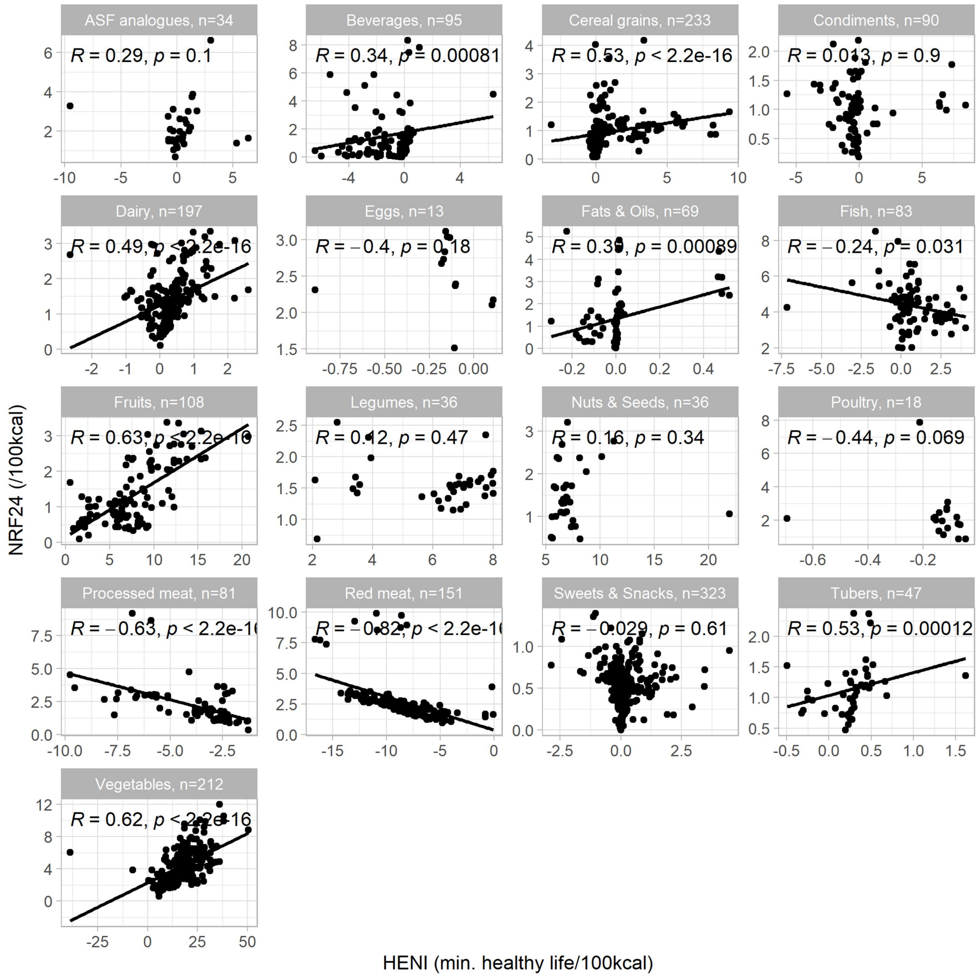

FIGURE 2
Correlation between NRF24 and HENI scores per 100 kcal for individual food items per food group; n = number of food items included in each food group. Spearman rho (*R*) and *p*-values included and best fit lines shown for statistically significant correlations ($p < 0.05$).

correlation was not strong enough to assume NRF9.3 would suffice as an indicator for both nutrient density and disease burden.

3.4 Application in nLCA

3.4.1 Classification based on nutrition indicators

Food items were categorized into "+/+" (NRF24 ≥ 1.2 and HENI≥0), "−/−" (NRF24 < 1.2 and HENI<0) or "+/−" (NRF24 < 1.2 and HENI≥0 or vice versa) categories to gain insight how food items and food groups are performing for both nutrition indicators. We found that most of the assessed food items fell in the "+/+" category (44% of all food items) and the least in the "−/−" category (11% of all food items) (Table 1). Food items that had a high nutrient density but also a high disease burden mainly fell in the food groups red meat and processed meat. Food items with a low nutrient density but a low disease burden were mainly represented by the food groups Cereal grains and Tubers. A large share of food items in the food group Sweets and Snacks also had a low nutrient density and a HENI≥0, although the HENI scores were close to 0. Sweets and Snacks may contain whole grains, nuts, milk, fruits or polyunsaturated fatty acids which gives them an advantage in the HENI score. More so, added sugar is only considered in the HENI score in the case of sugar sweetened beverages – which is globally the largest share of sugar intake (Malik and Hu, 2022) – and therefore Sweets and Snacks are not penalized for their sugar content. This categorization can be used in nLCA as an initial tool to identify health consequences of food items that are preferably avoided from an environmental perspective, e.g., "+/+" foods that have a high environmental impact. Such food items may require a more detailed evaluation before determining their role in a healthy and sustainable diet, depending on the specific context. For example, strawberries would require a high water use per 100 kcal and have a relatively high GWP while at the same time performing well on nutrition-based indicators (Figure 4). Honey, on the other hand, has a low environmental impact but scores low for nutrition-based indicators (Figure 4). Overall, Figure 4 shows that, for the selection of food items assessed, those with the lowest nutrient density and disease burden (red) relatively have lower environmental impacts (left lower corner). Animal source foods had a low water use compared to plant source foods but LU was variable with the highest LU observed for veal and smoke-dried beef.

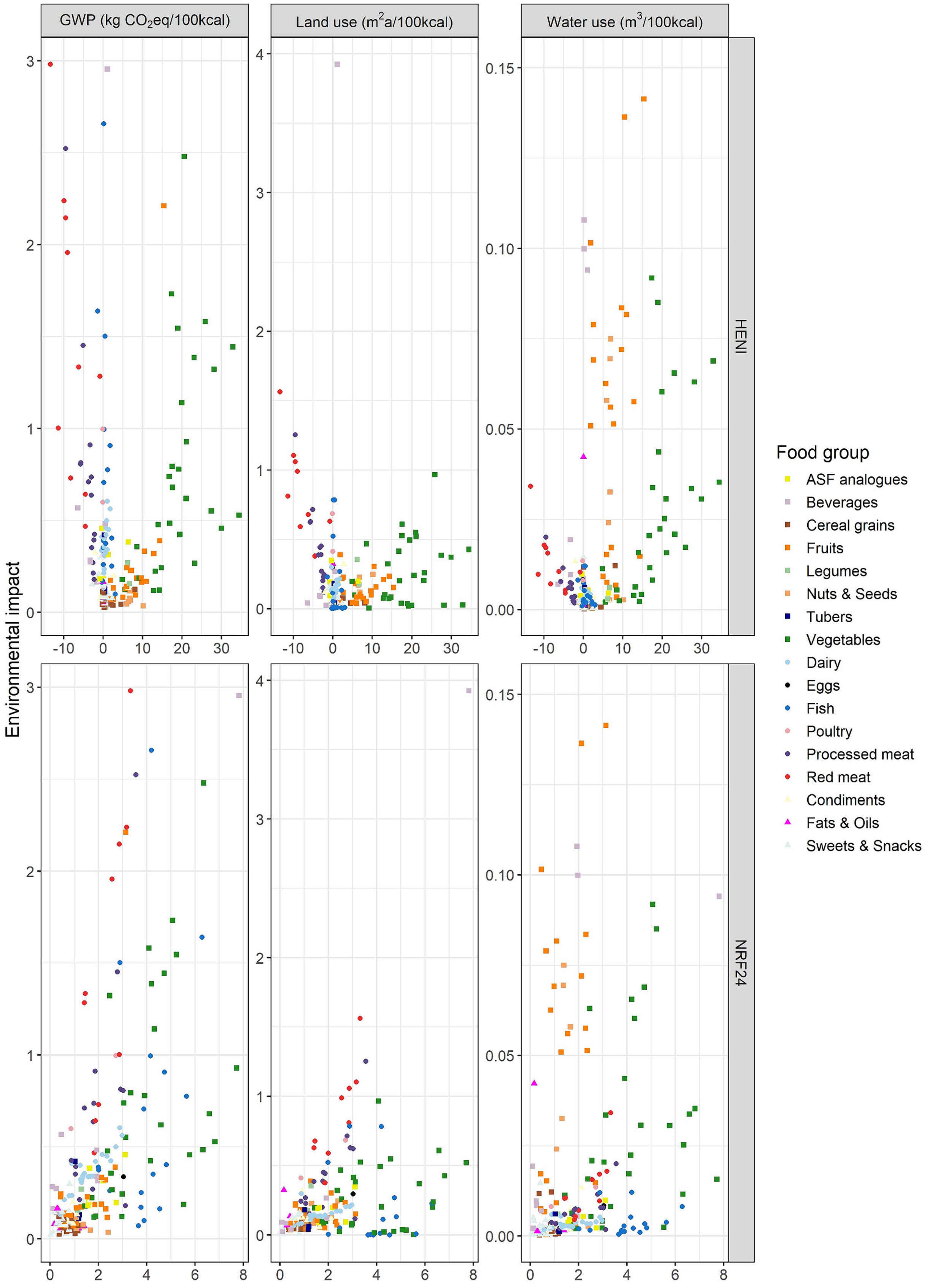

FIGURE 3
Correlation between nutrition-based indicators (horizontal grids) and environmental impact indicators (vertical grids) per 100 kcal for individual food items. GWP = Global Warming Potential. Shapes: circles indicate animal-source food items, squares indicate plant-source food items, triangles indicate mixed-source food items.

TABLE 1 Classification of individual food items based on NRF24 and HENI scores in food items per food group and percentage of food items per food group.

Food group	NRF > 1.2 & HENI < 0 (+/−)		NRF > 1.2 & HENI > 0 (+/+)		NRF < 1.2 & HENI < 0 (−/−)		NRF < 1.2 & HENI > 0 (−/+)	
	No.	%	No.	%	No.	%	No.	%
ASF analogues	13	38%	19	56%	2	6%	1	3%
Beverages	19	20%	18	0%	45	47%	13	14%
Cereal grains	6	3%	49	21%	67	29%	111	48%
Condiments	19	21%	5	6%	54	60%	12	13%
Dairy	24	12%	89	45%	16	8%	68	35%
Eggs	11	85%	2	15%	0	0%	0	0%
Fats and oils	10	14%	20	29%	17	24%	23	33%
Fish	20	24%	63	76%	0	0%	0	0%
Fruits	0	0%	45	42%	0	0%	63	58%
Legumes	0	0%	32	89%	0	0%	4	11%
Nuts and seeds	0	0%	23	64%	0	0%	13	36%
Poultry	15	83%	0	0%	3	17%	0	0%
Processed meat	58	72%	0	0%	23	28%	0	0%
Red meat	147	97%	0	0%	4	3%	0	0%
Sweets and snacks	3	1%	0	0%	134	41%	186	58%
Tubers	2	4%	16	34%	6	13%	23	49%
Vegetables	2	1%	208	98%	0	0%	2	1%

No. = number of food items.
% = percentage of food items of the food group.

3.4.2 Nutrition-based indicators as complementary functional unit

Using nutrition-based indicators as complementary functional units is a method to integrate the nutritional performance of food items into the LCA results. However, the downside of using a nutrition-based indicator with a value below zero as complementary functional unit is that it may lead to wrong interpretation of the LCA result, i.e., a negative value would erroneously suggest positive environmental impacts (Supplementary Figure 7). Negative HENI scores were in this case rescaled so that the lowest value was 0. By using the nutrition-based indicators as complementary functional unit, the relative performance of individual food items may shift. For example, while the values for all environmental indicators go down for almonds when using NRF24 as complementary functional unit, the values for apples increase for all environmental indicators expressed on NRF24 (Figure 5). Such an integrated assessment may be useful to simplify a comparison of relative environmental impacts between food items while taking the function of food into account (Sonesson et al., 2019).

4 Discussion

4.1 The complementarity of nutrient density and disease burden

The results of this study confirm our hypothesis that for individual food items, essential nutrient density and disease burden are independent indicators. That is, a high nutrient density does not directly imply a low disease burden or vice versa. This was supported by an overall weak correlation between NRF24 and HENI of $r = 0.32$ but with high variation between food groups (Figures 1, 2). Although data sources used were specific for the Netherlands, dietary risks have also been calculated for the US (Stylianou et al., 2021) and for Switzerland (Ernstoff et al., 2020) and we expect the lack of correlation between nutrient density and disease burden to exist regardless of the data source for nutrient content, dietary risk exposure or observed burden.

4.2 Identifying trade-offs in healthy and sustainable food consumption

Assessing indicators that provide unique information helps to identify trade-offs and rebound effects of food consumption choices, and of the encouragement of such choices through policy instruments (Masset et al., 2015; Saarinen et al., 2017; Walker et al., 2019). The high positive correlation between NRF24 and GWP ($r = 0.69$) suggests that food items with a higher nutrient density have a higher global warming potential (Figure 3). On the other hand, products with both a very low and very high HENI had a higher GWP. This contradicts the suggestion that changing toward a healthy diet inherently reduces the overall impact of the diet (Stehfest et al., 2009; Springmann et al., 2016) but is in line with others (Payne et al., 2016; Saarinen et al., 2017). Our results can confirm that there are certain food products that are "+/+" and some that are "−/−" and thus in- or decreasing those in the diets can lead to synergic benefits for human and planetary health (Table 1). Thus, when diets are far from optimal with a high "−/−" content, synergies can be expected when these foods are replaced with "+/+" foods (Westhoek et al.,

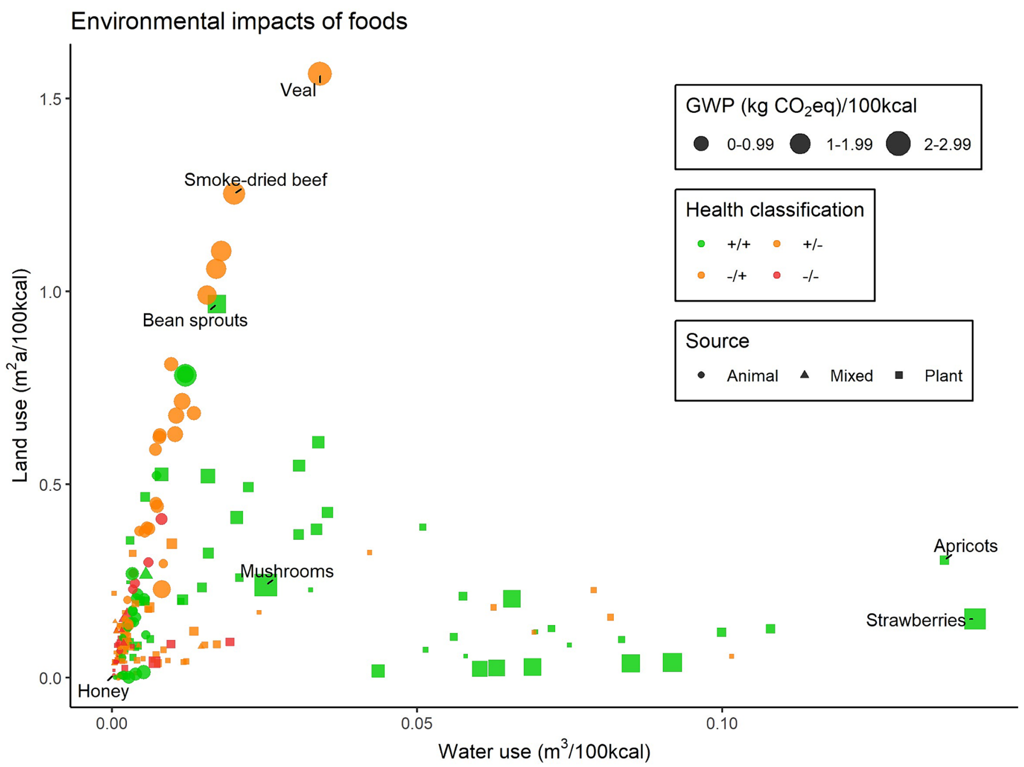

FIGURE 4
Relation between nutrition-based indicators and environmental impact indicators. Colors indicate the classification of food items based on NRF24 and HENI scores. +/+ = NRF24 ≥ 1.2/HENI≥0, +/− = NRF ≥ 1.2/HENI<0, −/+ = NRF24 < 1.2/HENI≥0, −/− = NRF24 < 1.2/HENI<0. Shapes indicate the source (animal, plant or mixed), size of the shape indicates global warming potential per 100 kcal.

2014; Stylianou et al., 2021). In this context, focusing on nutritious diets that are low in dietary risk factors such as trans-fatty acids, sugar sweetened beverages and processed meat is urgently needed to reduce diet-related diseases and obesity. This focus is also applicable to low-income countries where current diets suffer from nutrient inadequacy (Han et al., 2022). In this regard, some studies have shown that there is a point to which health and environmental impact can be improved simultaneously when current diets are far for optimal, while the trade-offs between health and environment appear mainly when it comes to marginal changes within diets (Stylianou et al., 2021; Heerschop et al., 2023). Moreover, the synergic environmental and health benefit from a reduction of animal source foods is also dependent on the functional unit used, e.g., water use in our study is relatively high for 100 kcal of fruits and vegetables, and will even be higher when expressed on protein content, but when expressed on a mass base, these food groups perform relatively well (Sokolow et al., 2019). To complicate things further, unsustainable consumption is not limited to the types of food consumed but also the extent of overconsumption and food waste, two aspects that are positively associated with the environmental impact of the diet (BajŽelj et al., 2015).

4.3 Food items in the dietary context

Assessments on a food item level can enable stakeholders to create advice or regulations that have shown to be effective for both consumers as well as industry practices (Shangguan et al., 2019). However, food items are not consumed in isolation but together in a meal, as part of a whole diet. Some food items may score low on nutrient density but may be important for the overall dietary quality because they provide unique nutrients that cannot be provided by other foods. Additionally, food items may contain safe amounts of a certain nutrient while a combination of multiple foods in a diet would risk exceeding a threshold above which the nutrient intake becomes detrimental, i.e., as would be the case for sodium or copper. Measuring the health impact of a diet requires a different approach and will lead to different outcomes than assessing the health impact of individual food items. To this regard, it has been shown that nutrient density of the whole diet is associated with modestly lower risks of chronic diseases and all-cause mortality (Chiuve et al., 2011), which contradicts some of our results on food item level. On the other hand, when reporting one score on dietary level, "+/+" food items elevate the score and can thereby make up for "−/−" food items. Therefore, to include the dietary context, a two-step LCA analysis could be useful, where data on individual food item level is assessed first, and the results are then combined into a daily diet (Sonesson et al., 2017).

4.4 Methodological choices for nutrition-based indicators

Methodological choices largely impact the interpretation of data (Conrad et al., 2020), e.g., related to the nutrients selected for nutrient profiling models, the choice of reference unit or how food groups are defined. Firstly, most commonly-used nutrient profiling models include

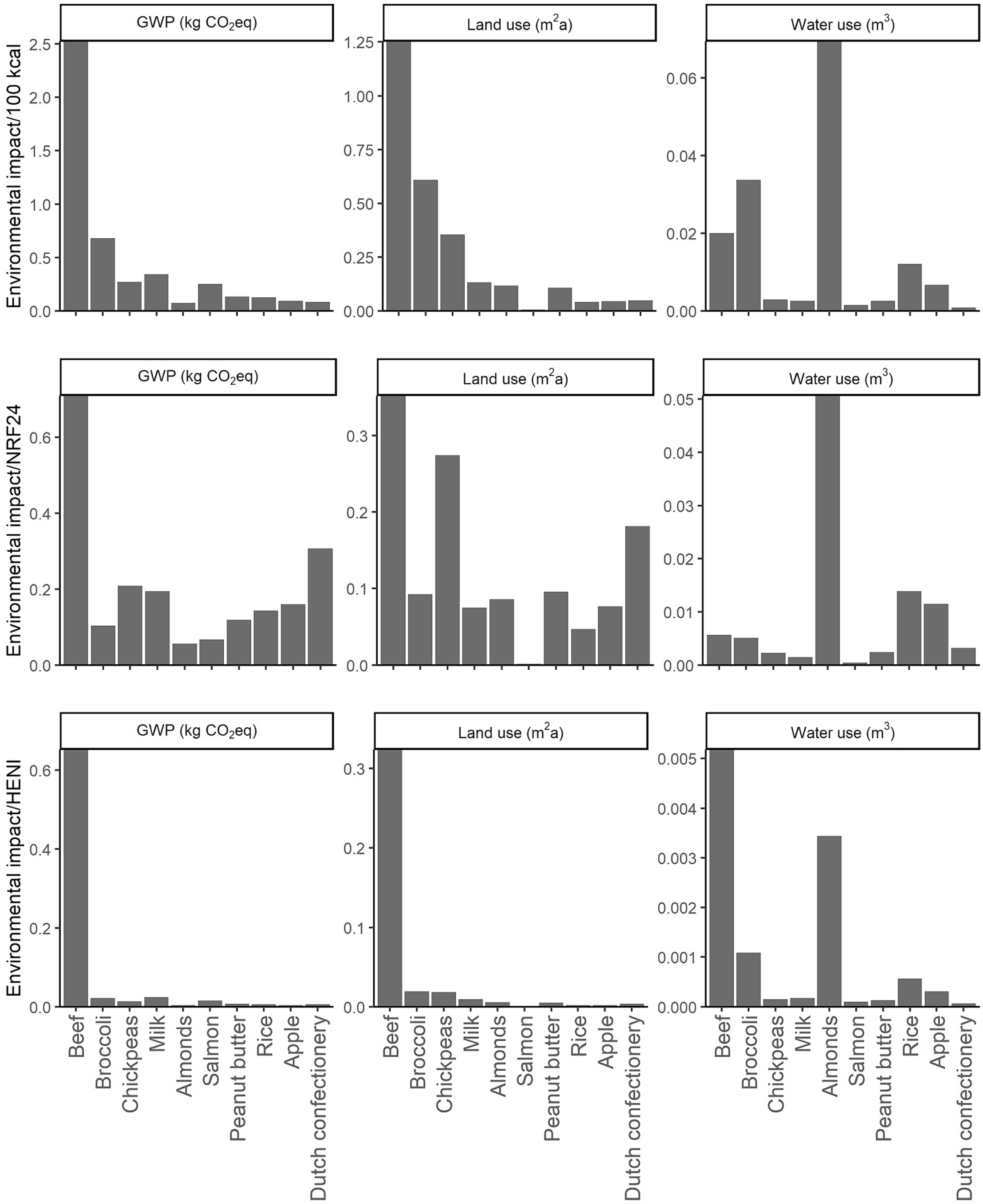

FIGURE 5
Environmental impacts expressed per 100 kcal (top), NRF24 (middle) or positively scaled HENI (bottom) for a selection of ten food items. GWP, Global Warming Potential.

health risks from, e.g., components like fiber, sugar, saturated fat, carbohydrates, cholesterol, flavonoids or omega-3 fatty acids, which are not considered essential nutrients (Bianchi et al., 2020). We showed the value of using a nutrient density score that includes a wide range of essential nutrients, i.e., those nutrients that cannot be synthesized by the human body at all or not in sufficient quantities and should therefore be sourced from food (Challem, 1999). However, only including beneficial nutrients also makes the need for using a complementary indicator for disease burden greater as otherwise detrimental health impacts are overlooked. Generally, the choice of nutrient profiling model depends on the aim of the study but when both nutrient density and disease burden are considered side-by-side, overlap between two scores should be avoided to minimize double rewarding or penalization. This overlap is reflected in the stronger correlation between nutrient density and disease burden for all food items together, as well as for most food groups, when NRF9.3 was used instead of NRF24 (Supplementary Figure 6). Furthermore, a narrow selection of nutrients can limit the comparison of food items over a wide variety of food groups (McAuliffe et al., 2020) and it has been recommended to include as many essential nutrients as possible in nLCA (Jolliet, 2022). Therefore, a nutrient density score specific for essential nutrients that avoids overlap with health risks but still covers a wide range of nutrients can provide relevant information on individual food items. However, it should be noted that the calculations of both NRF24 and HENI included some nutrients that are both essential and have a positive association with NCDs – i.e., calcium, omega-3 fatty acids. We thereby assumed that health impacts related to inadequate nutrient intakes are independent from health impacts from an insufficient intake of these dietary risk components. However, there is currently no underlying evidence for this assumption which means using NRF24 alongside HENI may double count health effects from calcium and omega-3 fatty acids.

Secondly, the choice of reference unit changes nLCA output values. In our study, the calculation on energy basis favors the nutritional impact and disfavors environmental impact of low energy foods, such as fruits vegetables. That is, reaching 100 kcal for low energy foods will require a higher volume of production and consumption and thereby higher benefits for human health and a higher environmental impact. Generally, expressing nutrient density on an energy basis is in favor as it represents the ratio of nutrients to energy which plays an important role in healthy dietary patterns. In addition, calculating scores on a mass- or serving basis, decreases the NRF24/HENI correlation for beverages and dairy, while increasing the correlation for eggs, legumes, nuts and seeds, and spreads and sauces (Supplementary Table 7), which is partly explained by the negative relation between serving size and energy density (Drewnowski et al., 2009). This emphasizes the importance of communicating the results using different reference units or clearly supporting the choice of a certain reference unit.

Thirdly, a unified definition of food groups is lacking. We found both positive and negative correlations ranging from very weak to strong, depending on the food group. These correlations would change depending on how food groups are selected. If the aim is to draw conclusions for entire food groups based on nLCA results, it would be necessary to have a common definition on how food items should be categorized. In addition, we observed large variability within food groups suggesting that conclusions for entire food groups may be reductive.

4.5 Limitations and uncertainty

Building on the previous section, we acknowledge that statements about the role of food items, or food groups, in healthy and sustainable diets rely on how data is interpreted on the one hand but also on which input data is used to draw conclusions. Estimating health and environmental impacts of food consumption involves a high level of uncertainty due to the uncertainty of input data. This can be related to, for example, unreliable dietary reporting and confounding factors (Gibney et al., 2020) but also to how environmental impact data is established. Additionally, associations between food consumption and the development of NCDs may be debated, not well understood, or not yet identified (Gibson et al., 2009; Lescinsky et al., 2022). On top of this, the GBD identifies health risks on a dietary level while the HENI brings these back to food item level. This emphasizes the aim of this study which was to highlight the importance of assessing both essential nutrient density and disease burden in nLCA by evaluating how these two factors of food consumption are associated, as opposed to drawing hard conclusions about the role of certain food items, or food groups, in healthy and sustainable diets.

4.6 Implications for policy

This finding has implications for the methodology on how the performance of food items are evaluated in regards to healthy and sustainable diets, e.g., through the use of an nLCA. In addition, we showed that both nutritional- and environmental impact indicators show large variability among individual food items, and it may be difficult to draw general conclusions for food groups as this will depend on how the food groups are defined, thus the importance to provide food specific evaluations. Overall, the health impact from food consumption is a complex issue and it is important to assess the extent to which simplified indicators reflect this complexity. In other words, there may be more value of showing multiple indicators side-by-side as opposed to combining multiple indicators into one value. On the other hand, the latter may be desired from a policy perspective to communicate sustainability information to consumers, e.g., through food labelling (Brown et al., 2020). Although nLCA would be an appropriate tool to support food labelling, combining multiple indicators risks losing important information and may subsequently not provide the accurate information and confuse consumers, thus the interest to use common units such as DALYs or minutes of life lost across all food items and risk factors that can be understood by the population and possibly lead to behavioral changes (Pink et al., 2022). Categorization or labeling is further complicated by the fact that there are no generic cut-off values to define which environmental impacts can be considered "high" or "low" (Bunge et al., 2021). Food labeling has, however, potential in providing consumers with information and has shown to be effective (Potter et al., 2023). Therefore, while methods are being refined, food labeling can be a way to encourage the consumption of products that are beneficial on most, if not all, indicators.

4.7 Assessing radically different diets

The methodology used in this study is useful for assessing marginal dietary shifts, i.e., interchanging food items. This approach assumes that dietary changes occur within the same food environment, producing the same foods with similar production methods. For short-term solutions, it is useful to identify dietary shifts that stay close to current dietary patterns because these shifts will be more accepted by consumers. However, the gains made with such changes are also marginal, both from a human health and planetary health perspective. Therefore, if the aim is to radically redesign food systems for long-term sustainability and to achieve bigger gains, the data used to calculate the health scores and impact indicators in this study, are no longer valid. The DRFs for calculating HENI scores are based on current exposure to dietary risk and current food intake. Moreover, LCA data is calculated assuming the current production systems and, often, an average value for one product is used while no distinction is made in how the food item is produced, e.g., cattle in feedlots fed with a lot of products humans can also consume versus cattle grazing on marginal lands (de Vries and de Boer, 2010; van Zanten et al., 2018).

5 Conclusion

This study stresses the importance of addressing essential nutrient content and disease burden of single food items individually in nLCA. The side-by-side calculation of a nutrient density indicator that exclusively included essential nutrients and an indicator for disease burden, showed useful to represent complementary information about food items' nutritional impact. This was supported by the fact that, across all assessed food items, no correlation was observed between the two indicators, and therefore a high nutrient density does not directly imply a low risk for non-communicable diseases, or the other way around. This may be more relevant for some food groups than for others. In addition, trade-offs and synergies between nutrition and environment are also different for nutrient density and disease burden, with a high variety for individual food items. Our results therefore do not support the statement that changing towards a healthy diet inherently reduces the overall environmental impact of the diet. Moreover, the findings contribute to the methodological discussions in the field of nLCA because focusing on single indicators or aggregating multiple indicators into one can lead to the risk of missing important information and may lead to wrong conclusions.

Data availability statement

The raw data underlying the conclusions made in this study are provided as Supplementary Data 2 and can be found in the publicly accessible repository Figshare (10.6084/m9.figshare.24223345). The LCA data used for this study is publicly available via https://www.rivm.nl/documenten/database-milieubelasting-voedingsmiddelen. The nutrient content data was extracted from the NEVO database, which is publicly accessible via https://nevo-online.rivm.nl/. All other relevant data underlying the conclusions made in the manuscript are contained within the article and the Supplementary Data 1, further inquiries can be directed to the corresponding author.

Author contributions

RC: Methodology, Visualization, Writing – original draft. EV: Methodology, Writing – original draft, Writing – review & editing. OJ: Methodology, Writing – review & editing. HZ: Supervision, Writing – review & editing. TH: Methodology, Supervision, Writing – review & editing.

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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.

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Supplementary material

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EDITED BY
Rakesh Bhardwaj,
Indian Council of Agricultural Research (ICAR), India

REVIEWED BY
Lenka Kourimska,
Czech University of Life Sciences Prague, Czechia
Jun Wang,
Jiangsu University of Science and Technology, China

*CORRESPONDENCE
Carlos Granados-Echegoyen
granados.echegoyen@yahoo.com
Alfonso Vásquez-López
avasquez@ipn.mx

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Brief overview of edible insects: exploring consumption and promising sustainable uses in Latin America

Carlos Granados-Echegoyen[1]*, Alfonso Vásquez-López[2]*, Nancy Calderón-Cortés[3], Heidy Lorena Gallego-Ocampo[4], Carlos Humberto Gómez-Rodríguez[5], José Manuel Rodríguez-Vélez[6], Mariza Araceli Sarmiento-Cordero[6], Leidy Julieth Salamanca-Canizales[4], Beatriz Rodríguez-Vélez[6], Fabián Arroyo-Balán[7] and Petra Andrade-Hoyos[8]

[1]CONAHCYT—Instituto Politécnico Nacional (IPN), Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional (CIIDIR), Campus Oaxaca, Santa Cruz Xoxocotlán, Oaxaca, Mexico, [2]Instituto Politécnico Nacional (IPN), Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional (CIIDIR), Campus Oaxaca, Santa Cruz Xoxocotlán, Oaxaca, Mexico, [3]Escuela Nacional de Estudios Superiores Unidad Morelia, Universidad Nacional Autónoma de México (UNAM), Morelia, Mexico, [4]Escuela de Ciencias Básicas, Tecnología e Ingeniería ECBTI, Universidad Nacional Abierta y a Distancia UNAD, Bogotá, Colombia, [5]Chemistry Department, University of Valle-Yumbo, Valle del Cauca, Colombia, [6]Departamento de Control Biológico, Centro Nacional de Referencia Fitosanitaria, Tecomán, Mexico, [7]CONAHCYT—Universidad Autónoma de Campeche, CEDESU, San Francisco de Campeche, Campeche, Mexico, [8]Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias (INIFAP), Campo de Experimental Zacatepec, Zacatepec de Hidalgo, Mexico

This review explores the significance of consuming edible insects, as well as their use in the food industry, agro-industry for animal husbandry, agricultural fertilizers and bio-pesticides, and pharmaceuticals. It emphasizes the increasing interest and relevance of this practice. The study starts by investigating the earliest evidence of anthropoentomophagy, which is the consumption of insects by humans, in the region. The review offers an overview of the consumption and utilization of insects in specific regions of the world, emphasizing their significance in various cultures and geographic areas. It also identifies the types of edible insects commonly consumed in Latin American countries, such as Mexico, and explains their preparation and consumption. Furthermore, the review assesses the nutritional value of edible insects, emphasizing their potential as a valuable source of protein, vitamins, and minerals. It also explores the various promising applications of insects, including their role in the food industry, animal husbandry, production of agricultural fertilizers and bioprotectants, and even their potential in the pharmaceutical sector. Finally, the article highlights the significance of entomophagy in Latin America by exploring its historical origins, nutritional benefits, and potential applications in various industries.

KEYWORDS

food security, nutrition, Caribbean, list, distribution

1 Introduction

The demand for animal-based food and feed products is expected to increase significantly due to the projected global population growth, estimated to reach 9–11 billion by 2050. This will result in a significant increase of up to 70% in the demand for animal-based food protein to meet the dietary needs of the growing population (Varelas, 2019; Thornton et al., 2023). As the population continues to grow, there is an increasing need to explore sustainable and nutritious food sources (Hazarika and Kalita, 2023; Papastavropoulou et al., 2023). Insects play a critical role in meeting this demand as a sustainable and efficient food source. Compared to traditional protein sources, insects require fewer natural resources, such as water and land, for production. They also have a high feed conversion rate, efficiently converting consumed food into body mass, making them ideal for large-scale food production (Oonincx et al., 2015; Lange and Nakamura, 2023). Insects have long been a common part of the diet in many Asian, African, and Latin American cultures due to their nutritional content, providing a rich source of high-quality protein, essential amino acids, fiber, monounsaturated and polyunsaturated fats, as well as such as vitamins and minerals. Surprisingly, they offer a nutritional profile comparable to traditional animal protein sources such as beef or chicken (Dobermann et al., 2017; Orkusz, 2021; Khalifah et al., 2023). Insect consumption can also help address issues of malnutrition and nutritional deficiencies, especially in regions with limited food availability (Imathiu, 2020). There are several reasons why many people do not include insects in their usual diet, such as cultural factors, aversion to their appearance, association with pests (Sogari et al., 2022, 2023), unfamiliarity, stigmas and superstitions, and mainly ignorance about the advantages of its consumption (Yen, 2009; Tan et al., 2015; Hlongwane et al., 2020; Alhujaili et al., 2023). Nevertheless, there is a growing interest in consuming insects due to their potential as a sustainable food source. As awareness of their nutritional value and environmental benefits spreads, attitudes towards insects as a viable food option are gradually changing (Grabowski et al., 2022). Latin American countries have a rich cultural tradition of incorporating insects into their diet. This arises from their culinary heritage, where traditional techniques have been developed to prepare insects, considered a delicacy. The availability of a wide variety of insect species in both rural and urban areas contributes to their consumption, often including them in festivals and celebrations (Bermúdez-Serrano, 2020; Guiné et al., 2023; Tzompa-Sosa et al., 2023). The objective of this work is to highlight the usefulness and potential that insects represent, given their environmental, social, and health benefits.

2 Materials and methods

Academic publications are increasing at an accelerating rate. As a result, it is becoming increasingly challenging to keep pace with and comprehend the current state of specific fields. Several scholars argue that literature reviews are essential for synthesizing the current state of specific fields. A structured bibliographic review is a traditional approach to analyzing and assessing the published scientific literature. This type of review provides an in-depth analysis of the literature content, as demonstrated by Rousseau (2012), Wang et al. (2019), and Ghadimi et al. (2019). A review of pertinent research articles was conducted by searching prominent academic databases, including SCOPUS, Web of Science (WOS), MDPI, and PubMed, among others. To ensure an unbiased search, synonyms for the consumption of the specified insects were included. These synonyms included "edible insects," "entomophagy," and "anthropo-entomophagy," as well as the terms "protein sources" and "Latin America." In SCOPUS, the search query was "edible insect" AND ("consumption" OR "meal"). In Web of Science (WOS), the search queries included all fields, titles, abstracts, and author keywords using the phrase "insect consumption." The same search strategy was applied to all the databases utilized. Tables have been created to present information about the primary categories of edible insects in Mexico, the proximate nutrient composition, a comparison of proximate nutrient content within species of the same category, the fatty acid composition of specific edible insects, mineral content, a comparison of proximate nutrient content at different stages of development, and the antinutrient content of insect-based foods. Each table includes data on the distribution of species in the Americas and the Caribbean, supported by the Global Biodiversity Information System (GBIF, https://www.gbif.org/es/). Database searches were last conducted and reviewed for relevant literature on December 22, 2023.

3 Entomophagy and Latin American consumption

Entomophagy, defined as the consumption of insects by humans, falls under the term anthropoentomophagy when insects are consumed as food or in products like honey and propolis (Costa-Neto and Ramos-Elorduy, 2006; Ramos-Elorduy, 2009; Dagevos and Taufik, 2023). Although early human entomophagy has received limited research attention due to preservation challenges, various studies employing tools, residues, DNA, coprolites, dental wear, stable isotopes, osteology, and cave paintings contribute valuable insights (McGrew, 2014). Evidence suggests that early hominids engaged in the search for and consumption of termites for nearly a million years during the Plio-Pleistocene period. Wear patterns on bone tools used by *Paranthropus robustus* to extract termites from mounds support this hypothesis (Backwell and d'Errico, 2001). Coprolite analysis in the United States indicates that 4,500 years ago, humans collected and consumed *Melanoplus sanguinipes* grasshoppers (Madsen and Kirkman, 1988). Chitinous insect exoskeletons have been found in coprolites of prehistoric humans in the United States, Mexico, and Peru (Reinhard and Bryant, 1992; Brothwell and Brothwell, 1998). Dental plaque studies on a 1.2 million-year-old hominid in northern Spain revealed microfossils of insect fragments (Hardy et al., 2016). Fossil studies in South Africa propose insect consumption as a potential explanation for high strontium/calcium levels in the dental enamel of the *Australopithecus* genus, existing 2 to 4 million years ago (Sponheimer et al., 2005). Insect consumption during periods of fruit scarcity may have influenced hominid intelligence evolution, providing minerals like iron and omega-3 fatty acids (Kyriacou, 2014; Melin et al., 2014).

Human insect consumption dates back to prehistoric times, evident in archaeological and anthropological findings across diverse cultures worldwide. In Latin America, countries like Mexico, Peru, Colombia, Venezuela, and Ecuador have a notable history of insect consumption, contributing to food security for local communities.

Depending on the species and development stage, these insects are rich sources of proteins, fats, carbohydrates, and minerals (Costa-Neto, 2015). Insects, with their substantial biomass, have a historical association with human consumption, even being mentioned in sacred texts like the Bible and the Quran (Ramos-Elorduy and Viejo-Montesinos, 2007). Certain insect species, including cochineal insects, ants, and wasps, were cultivated long before the arrival of the Spanish to the American continent (Costa-Neto, 2015). In Aztec culture, insects were used as a tribute to emperors, and pre-Hispanic delicacies like escamoles (ant larvae) continue to be consumed as exotic dishes in Mexico. The maguey worm holds a prestigious place in Mexican gastronomy, featuring various dishes incorporating roasted, fried, or stewed insects with aromatic herbs (Ramos-Elorduy, 2004). Onore (1997) documented 83 edible species in Ecuador, and Costa-Neto and Ramos-Elorduy et al. (2006) noted 95 species used by 39 ethnic groups in Brazil (Costa-Neto, 2015). In Colombia and Venezuela, palm worms are prominently consumed, while in Peru, there is a tradition of consuming large black crickets in the Ayacucho region (Ramos-Elorduy and Viejo-Montesinos, 2007). Entomophagy in Brazil dates back to the 16th century, with indigenous peoples already consuming various insects during early European colonization. This practice has become ingrained in Brazilian culinary traditions (Costa-Neto and Ramos-Elorduy, 2006).

Insects can be consumed directly at different developmental stages or indirectly through insect-derived products like propolis, honey, pollen, wax, and royal jelly. Throughout history, non-stinging bee products, such as those used by the Mayan and Aztec civilizations, played a significant role in socioeconomic and religious activities. The Aztecs even used honey for trade with Spanish colonizers in the 16th century. Similarly, native communities in Brazil, Paraguay, Uganda, Madagascar, the Himalayas, and Australia have incorporated bee products into their traditions and cultures over time (Gupta et al., 2014; Cumo, 2015; Grüter, 2023). Grüter (2023) highlights the medicinal use of *Lepidotrigona arcifera* honey by Nepalese individuals in India and the therapeutic applications among Ugandan pygmies, who utilize it as a remedy for constipation. Calderón-Fallas et al. (2021) emphasize the sacred significance of bees, particularly the Mayan bee (*Melipona beecheii*), in spiritual, cosmological, and mythological contexts. Costa-Neto (2015) and Medeiros (2014) present an overview of edible insects in Latin America, with Mexico leading at 415 species (56.46% of the total) and Brazil following closely with 122 species (16.6% of the total). The diverse culinary traditions and entomophagy practices across Latin American countries contribute to a rich tapestry of cuisine, totaling 735 edible insects.

The modernization of bee-derived product marketing has led to meliponiculture, involving the breeding and care of bees from the Meliponini tribe (Álvarez, 2016; Cortes-Martínez et al., 2021). This practice, primarily carried out by indigenous cultures and producers in the Neotropics, focuses on species such as *M. beecheii, M. eburnea, M. quadrifasciata, M. scutellaris*, and *Tetragonisca angustula* (Jaffé et al., 2015; Quezada-Euán et al., 2018; Quezada-Euán and Alves, 2020). Meliponiculture, a valuable biocultural heritage, has been consistently practiced for approximately 2000 years, particularly with *M. beecheii* in Mesoamerica (Nates-Parra and Rosso-Londoño, 2013; Grüter, 2023). In traditional medicine, products derived from stingless bees, particularly *T. angustula*, are employed for treating skin and eye diseases. These products have also shown effectiveness in addressing respiratory and digestive ailments, attributed to the antibiotic properties of hydrogen peroxide and gluconic acid present in honey. Additionally, honey is recognized as a natural food source that may help prevent certain types of cancer associated with oxidative stress on physiological cells in humans (Kumul et al., 2015). Stingless bee honey, along with honey from *Apis mellifera*, plays a role in the preparation of alcoholic beverages. Pollen derived from these bees is occasionally used as a protein supplement in food. Moreover, in Mexico, Brazil, Ecuador, and Paraguay, bee larvae and pupae are consumed as sources of protein and vitamins (Grüter, 2023). Apicultural products and alcoholic beverages made from honey have gained popularity in Latin American markets, valued as artisanal products that offer natural and healthy nourishment.

Latin America holds the second-highest market value for edible insects globally, reaching $92.2 million, with expectations of nearly tripling to $250.6 million by 2030. This projection, close to the estimated European market value of $261.5 million, highlights the region's attractiveness to both local and international traders, with Mexico particularly standing out. Mexico's market value was reported at $26 million in 2018, with an 18% annual growth rate, projected to reach $59 million by 2023. North America, especially the United States, is also experiencing growth, making it an intriguing market for Hispanic entrepreneurs (Research and Markets, 2018; Bermúdez-Serrano, 2020; Guiné et al., 2021). Insects offer a wide range of benefits in various areas, including food, medicine, spiritual and religious rituals, cosmology, mythology, art, economics, and culture. These diverse uses have contributed to the continued use and consumption of insects by indigenous and local communities over the years (Costa-Neto, 2015; Van Huis et al., 2022). In addition, certain insects used as aphrodisiacs have influenced people from various cultures (Costa-Neto and Ramos-Elorduy, 2006). Omuse et al. (2024) compiled a comprehensive list of 2,205 identified species of edible insects. Beetles are the largest category of edible insects, comprising 468 species. Hymenoptera ranks second with 351 species, followed by Orthoptera with 267 species and Lepidoptera with 253 species (Costa-Neto and Ramos-Elorduy, 2006). According to Jongema (2017), the majority of these edible insect species are concentrated in tropical countries. These edible insects can be categorized as follows: beetles (31%), caterpillars (17%), ants, bees, and wasps (15%), grasshoppers (13%), bugs (11%), dragonflies (3%), termites (3%), cockroaches (2%), spiders (1%), and other unspecified species (2%).

In Latin American countries, the consumption of insects is influenced by both the accessibility of these food sources and their cultural significance. Insects are commonly prepared using various methods such as frying, roasting, or as ingredients in traditional dishes. Beyond their nutritional benefits, entomophagy may hold cultural and symbolic importance within specific communities (Ong'Or et al., 2024). For example, when considering experiences in other parts of the world, such as Africa, a wide variety of insects are consumed, including termites, caterpillars, grasshoppers, and crickets. These insects are collected from the wild or reared on a small scale for consumption (Womeni et al., 2009; Pal and Roy, 2014; Kipkoech et al., 2023). In Asia, especially in countries like Thailand, Cambodia, and Laos, edible insects are considered a culinary delicacy. Some popular insect species include silkworms, beetles, bees, and ants. In addition to being part of the local diet, insects have also become tourist attractions, as visitors can sample various dishes prepared with insects (Hanboonsong et al., 2013; Durst and Hanboonsong, 2015; Krongdang et al., 2023). In Europe and North America, although the consumption of insects is not yet widespread, it has gained popularity in recent years. Insect-based products can be found in specialty stores, such as cricket flour for making bread or energy bars containing beetle larvae (Reverberi, 2021; Skotnicka et al., 2021). Currently, edible insects serve as a nutrient-rich food source in many parts of the world, and their consumption is gaining acceptance and popularity due to their sustainability and nutritional value.

In Mexico, 415 species of insects have been documented as being consumed by various ethnic groups throughout the country (Ramos-Elorduy et al., 2003; Ramos-Elorduy and Pino, 2005). Of the total, 83% of these insects are terrestrial, while 17% come from continental aquatic ecosystems. Furthermore, it has been observed that 55.8% of these species are consumed in their immature stages, such as eggs, larvae, pupae, and nymphs, while 44.2% are consumed in their adult state. It is important to note that certain species are consumed at any stage of their development (Costa-Neto and Ramos-Elorduy, 2006). There are species with esteemed reputations and flavors that are highly valued in national and international markets. However, their exploitation is unregulated, which can have environmental consequences (Ramos-Elorduy et al., 2003 and Table 1). Currently, the consumption of insects has evolved from a local or regional practice to a significant commercial and agro-industrial phenomenon (Montalbán et al., 2022). For example, Black soldier fly (BSF) and mealworm larvae are commercially available for feeding ornamental fish in the market (Thrastardottir et al., 2021).

In Latin America, the potential uses of edible insects represent a unique opportunity to address several pressing issues, such as poverty eradication, food sovereignty, and sustainable development (Dossey et al., 2016). By embracing this innovative and culturally relevant food source, the region can create a competitive chain that not only improves livelihoods but also contributes to a more resilient and equitable food system. Establishing a competitive edible insect supply chain can create income opportunities, particularly in rural areas where poverty rates are high (Bermúdez-Serrano, 2020). Small-scale insect farming can be relatively inexpensive to start and maintain, offering a source of income for marginalized communities. However, this requires the support of local governments, which have a crucial role to play in promoting sustainable production and consumption of edible insects through supportive policies and regulations. This includes incentivizing insect farmers, investing in research and infrastructure, and raising awareness of the nutritional and environmental benefits of insect-based diets (Stull and Patz, 2020). Investing in research and innovation related to edible insects can lead to the development of new products and technologies, thereby enhancing the competitiveness of the insect value chain. This includes exploring alternative uses such as animal feed, pharmaceuticals, and sustainable packaging materials (Melgar-Lalanne et al., 2019). As global interest in sustainable and alternative protein sources grows, Latin America has the opportunity to position itself as a leader in the edible insects market. By capitalizing on its biodiversity and rich culinary traditions, the region can attract both domestic and international consumers.

4 Nutritional values of edible insects

From a nutritional standpoint, edible insects are a significant source of protein, fat, minerals, and fiber. However, the nutritional value of insects can vary depending on their habitat, the insect's diet, the edible stage of development (egg, larva, nymph, or adult), sex, and the type of processing they undergo, such as being consumed whole (dehydrated, boiled, roasted, fried, etc.). In addition, the storage of edible insects directly affects the content and availability of nutrients due to potential changes in the physicochemical properties of proteins and lipids (Cruz, 2017; Kulma et al., 2019; Cerisuelo, 2021). Not only is the quantity of proteins present in edible insects important, but also the quality of these proteins, depends on the amount of amino acids they contain. Edible insects can offer a range of essential amino acids, serving as a crucial supplement to address amino acid deficiencies in local staple foods. The orders Lepidoptera, Orthoptera, Coleoptera, and Diptera are characterized by high levels of glutamic and aspartic acid, phenylalanine, and alanine (Avendaño et al., 2020). On the other hand, the suborder Heteroptera (Hemiptera) is characterized by its high levels of proline, leucine, tyrosine, alanine, valine, and methionine. The percentage of protein in insects is expressed on a dry weight basis. Accordingly, the percentage of Coleoptera ranges from 20 to 71%, Diptera from 35 to 70%, Ephemeroptera from 37 to 68%, Hymenoptera from 10 to 81%, Lepidoptera from 13 to 78%, the suborders Sternorrhyncha and Archaeorrhyncha (Hemiptera) from 33 to 72%, Heteroptera from 36 to 71%, and Orthoptera from 27 to 77% (Ramos-Elorduy, 2004; Avendaño et al., 2020). Conventional foods have a lower protein content compared to insects. For example, eggs from birds, chicken, and pork typically contain protein amounts ranging from 68.9 to 75% of dry weight, with beef and fish being exceptions with a higher range (Ramos-Elorduy, 2004; Lizhang et al., 2008). On the other hand, insects also contain significant amounts of healthy unsaturated fats and essential fatty acids, which provide the necessary energy for protein assimilation (Ramos-Elorduy, 2004; Glover and Sexton, 2015).

In general, the fat content of insects ranges from 10 to 40% of dry weight, reaching 50% in Coleoptera and 77% in Lepidoptera (Lizhang et al., 2008; Van-Huis et al., 2021). According to Lizhang et al. (2008), in certain insect orders, the protein content tends to be higher than the fat content, being approximately twice as high. Insects with high protein content include Coleoptera, Lepidoptera, and Heteroptera (Hemiptera), followed by Sternorrhyncha and Archaeorrhyncha (Hemiptera), Hymenoptera, Diptera, and Orthoptera. Notably, there is a negative correlation between protein and fat content (Lizhang et al., 2008). Insects typically contain significant amounts of essential micronutrients, including copper, iron, magnesium, manganese, phosphorus, selenium, and zinc. They also provide smaller amounts of potassium and calcium. Some insects are a valuable source of specific vitamins, including A, C, D, E, K, and the B-complex (B1, B2, B3, B5, B6, B12, H) (DeFoliart, 1989; Ramos-Elorduy, 2004; Lizhang et al., 2008; Van-Huis, 2013; Van-Huis et al., 2021). However, despite the enormous potential of insects as a nutritious food (Kowalski et al., 2022), some people may experience allergic reactions to insect proteins. Allergic sensitivity can develop from prolonged exposure to insects and has been documented by entomologists. It is believed that individuals with pre-existing shellfish allergies may also experience cross-reactivity with insects, as crickets and shrimp are relatively close relatives. However, it is important to note that cross-reactivity is not inevitable (Glover and Sexton, 2015). On the other hand, it has been suggested that childhood exposure to chitin, the primary substance that forms the exoskeleton of insects, may enhance the immune system's response to intestinal parasitic infections and reduce certain allergic conditions

TABLE 1 Main groups of edible insects in Mexico and their distribution in Latin America and the Caribbean.

Order/Family	Insect	Local name	Consumption	Distribution in America	Reference
Hymenoptera					
Vespidae	*Brachygastra azteca*	"Vinitos" or "repletas"	Adult Cooked with chili and onion	Mexico	Ramos-Elorduy et al. (2006), Baigts-Allende et al. (2021), and Rumpold et al. (2014)
	B. mellifica			South USA, Mexico, Central America	
	Mischocyttarus basimacula			Mexico, Central America, South America	
	M. cubensis mexicanus			Southeastern USA, Mexico, Central America, South America, Caribbean	
	M. pallidipectus			Mexico, Central America, South America	
	Parachartergus apicalis			Mexico, Central America, South America	
	Polistes (Apanilopterus) canadensis			South USA, Mexico, Central America, South America	
	P. (Apanilopterus) instabilis			Mexico, Central America, South America, Caribbean	
	P. major			South and Southeastern USA, Mexico, Central America, South America, Caribbean	
	Polybia occidentalis nigratella			Mexico, Central America, South America	
Formicidae	*Liometopum apiculatum*	Escamoles (reproductive ant larvae)	Eggs	USA, Mexico	Ramos-Elorduy et al. (2003, 2006) and Lara-Juárez et al. (2015)
	L. occidentale var. *Luctuosum*			West and Southwestern USA, Mexico	
	Atta Mexicana	Chicatanas	Adult	South and Southwestern USA, Mexico, Central America and South America	Ramos-Elorduy et al. (2006)
	A. cephalotes			Mexico, Central America, South America and Caribbean	
	A. texana			Northeastern and South USA, Mexico and Caribbean	
Apidae	*Apis mellifera adansonii*	Honey bee, Stingless bee	Egg, Larvae, Pupa, Adult, Honey	Caribbean	Ramos-Elorduy et al. (2006)
	Lestrimelitta chamelensis			Mexico	
	Melipona beecheii			Mexico, Central America to Costa Rica and Caribbean	
	M. fasciata			Mexico, Guatemala, Costa Rica, Colombia	
	Scaptotrigona Mexicana			Mexico, Central America	
	S. hellwegeri			Mexico	
	Plebeia sp.			Southwestern USA, Mexico, Central America and South America	
	Nannotrigona testaceicornis			Mexico, Central America and South America	
	Trigona (Tetragona) jaty			South America	
	T. (Tetragonisca) angustula			Mexico, Central America and South America	
Driopinidae	*Neodiprion guilletei*	Saw fly	Eggs, Larvae, Pupa	South Canada, USA, Mexico	Pino and Ramos-Elorduy (2021)
	Zadiprion falsus (=vallicola)			Mexico	
Coleoptera					
Bostrichidae	*Prostephanus truncates*	Larger grain borer	Larvae	Southwestern USA, Mexico and Central America	Pino and Ramos-Elorduy (2021)
Buprestidae	*Chalcophora* sp.	Pine log worm	Larvae	USA, Mexico and Caribbean	Pino and Ramos-Elorduy (2021)

(Continued)

TABLE 1 (Continued)

Order/Family	Insect	Local name	Consumption	Distribution in America	Reference
Cerambycidae	*Arhopalus* sp.	Pine worm	Larvae, Pupa	North America and Caribbean	Pino and Ramos-Elorduy (2021)
Cicindlidae	*Habroscelimorpha curvata* (=*Cicindela curvata*)		Larvae	Mexico	Pino and Ramos-Elorduy (2021)
	Cicindela (*Cincidelidia*) *roseiventris*			Mexico, Central America	
Curculionidae	*Rhyncophorus palmarum*	Coconut palm weevil, Red agave worm "Botija" or "chatita" worms, Corn weevil	Larvae	South America	Ramos-Elorduy et al. (2006) and Pino and Ramos-Elorduy (2021)
	Scyphophorus acupunctatus			USA, Mexico, Central America and South America	
	Sitophilus sp.			North America (West and East Canada, USA and Mexico), Central America, South America and Caribbean	
Dytiscidae	*Cybister* sp.		Larvae, Adult	USA, Mexico, Central America and South America	Pino and Ramos-Elorduy (2021)
Gyrinidae	*Gyrinus parcus*	Whirlwind beetle	Larvae	USA, Mexico and Central America	Pino and Ramos-Elorduy (2021)
Melolonthidae	*Dynastes hylus*	Avocado trunk worms	Larvae	Mexico	Pino and Ramos-Elorduy (2021)
Noteridae	*Suphisellus* sp.		Larvae, Adult	South and Northeastern USA, Mexico, Cental America, South America and Caribbean	Pino and Ramos-Elorduy (2021)
Passalidae	*Passalus (Passalus) af. punctiger*	Rotten log worm	Larvae	North USA, Mexico, Cental America, South America and Caribbean	Pino and Ramos-Elorduy (2021)
Scarabaeidae	*Phyllophaga* sp.	Gallina ciega	Larvae	North America, Central America, South America and Caribbean	Pino and Ramos-Elorduy (2021)
Tenebrionidae	*Tenebrio molitor*	Yellow flour worm, meal worm	Larvae	North America, Central America (El Salvador), and South America	Pino and Ramos-Elorduy (2021)
Diptera					
Stratiomydae	*Hermetia aurata*	Soldier fly	Larvae	Mexico	Pino and Ramos-Elorduy (2021)
Lepidoptera					
Hesperiidae	*Aegiale hesperiaris*	White agave worm	Roasted insect larvae seasoned with chili and salt	Mexico	Ramos-Elorduy et al. (2006)
Noctuidae	*Helicoverpa zea*	Corn worm	Larvae	North America, Central America, South America and Caribbean	Ramos-Elorduy et al. (2006)
Bombycidae	*Bombyx mori*	Silkworm	Larvae	USA and South America	Pino and Ramos-Elorduy (2021)
Crambidae	*Laniifera cyclades*			Mexico	Ramos-Elorduy et al. (2006)
Cossidae	*Comadia redtenbacheri*	Salted mezcal worms, Mezcal worms, Chinicuiles, Red maguey worm	Larvae	South USA and Mexico	Ramos-Elorduy et al. (2006)
Danaidae	*Danaus plexippus*	Monarch butterfly	Larvae	North America, Cental America, South America and Caribbean	Pino and Ramos-Elorduy (2021)
Megathymidae	*Aegiale hesperiaris*	White maguey worm	Larvae	Mexico	Pino and Ramos-Elorduy (2021)
Nymphalidae	*Charaxes jasius*	"Cupiches," "Huenches," "Conduchas," "Chamas"	Pupa	Canada	Pino and Ramos-Elorduy (2021)
Pieridae	*Eucheira socialis*	Arbutus tree worm "cupiche"	Larvae	Mexico	Pino and Ramos-Elorduy (2021)

(Continued)

TABLE 1 (Continued)

Order/Family	Insect	Local name	Consumption	Distribution in America	Reference
Sessidae	*Synanthedon cardinalis*	Resin moth	Larvae	Mexico	Pino and Ramos-Elorduy (2021)
Orthoptera					
Pyrgomorphidae	*Sphenarium histrio*	"Chapoli," Chapulines		Mexico	Ramos-Elorduy et al. (2006)
	S. purpurascens			Mexico	
	S. magnum			Not Found in GBIF	
Acrididae	*Melanoplus femurrubrum*			North America	Ramos-Elorduy et al. (2006) and Pino and Ramos-Elorduy (2021)
	M. mexicanus			Canada, USA, Mexico	
	M. differentialis			USA, Mexico	
	Spharagemon equale			North America	
	Orphulella orizabae			Mexico	
	O. tolteca			Mexico	
	O. quiroga			Mexico	
	Orphulella sp.			North America, Cental America, South America and Caribbean	
Hemiptera					
Pentatomidae	*Brochymena (Arcana) tenebrosa*	Jumil sagrado "Xomitl," Jumil de Morelos, "Chumil"		North America, Cental America, South America and Caribbean	Ramos-Elorduy et al. (2006) and Pino and Ramos-Elorduy (2021)
	Chlorocoris sp.			South USA, Mexico, Cental America, South America and Caribbean	
	Edessa cordifera (syn. *Ascra cordifera*)			East USA, Mexico, Cental America, South America and Caribbean	
	Euschistus sulcacitus			Mexico and Costa Rica	
Notonectidae	*Buenoa margaritacea*	Ahuahutle, Axayacatl	Adults	USA and Mexico	Ramos-Elorduy et al. (2006)
Corixidae	*Corisella edulis*	Ahuahutle, Axayacatl	Adults prepared in tuna patties or as finger food	USA and Mexico	Ramos-Elorduy et al. (2006)
	C. mercenaria (*Corixa mercenaria*)			Not Found in GBIF	
	C. tarsalis			Canada and USA	
	C. texcocana			Not Found in GBIF	
	Graptocorixa abdominalis			South USA and Mexico	
	G. bimaculata			Mexico	
	Hesperocorixa laevigata			Canada and USA	
	Krisousacorixa azteca			Not Found in GBIF	
	K. femorata			Not Found in GBIF	
	Trichocorixa sp.			North America, Cental america, South America and Caribbean	
Notonectidae	*Notonecta unifasciata*	Ahuahutle, Axayacatl	Adults	North America	Ramos-Elorduy et al. (2006)
Coreidae	*Thasus gigas*	"Xamues," "Cocopaches"		South USA, Mexico, Cental America	Pino and Ramos-Elorduy (2021)
Membracidae	*Hoplophorion (Metcalfiella) monograma*	"Periquito del aguacate"		Mexico	Pino and Ramos-Elorduy (2021)
	Stictocephala bisonia			Canada and USA	
Aetalionidae	*Aetalion quadratum* (= *Aethalion quadripunctatus*)	Avocado greenfly		Mexico	Pino and Ramos-Elorduy (2021)
	A. nervosopunctatum			Mexico	
	A. quadratum			Mexico	

(Van-Huis, 2013). It is important to note that there is considerable variation in the nutritional composition of insect species depending on factors such as harvest location, processing methods, insect life stage, rearing techniques, and insect feed. Based on the available data (on a dry weight basis), it is suggested that specific treatments can enhance the nutritional content, aroma, appearance, and taste of edible insects. However, it is important to consider additional factors that may affect the content and composition of insects. The factors responsible for the nutritional content and quality of edible insects are not well understood. These factors include the chemical composition of insects, their handling and storage practices, microbial contamination, insect diet, feeding time, host plants, and phytonutrient content (Imathiu, 2020; Stull and Weir, 2023).

The following tables present comprehensive information on the nutrient composition of various insect orders, as documented in a study by Meyer-Rochow et al. (2021). Table 2 from Meyer-Rochow et al. illustrates the proximate nutrient composition of edible insects per 100 grams of dry matter. In Table 3, you will find a comparative analysis of the nutrient content among different species within the same genus, also presented per 100 grams of dry matter. Table 4 presents the amino acid composition of various species within the same genus. The fatty acid composition of various edible insects is presented in Table 5, while Table 6 displays the mineral content of selected edible insects, measured in milligrams per 100 grams. Table 7 presents a comparative overview of the nutrient content at various developmental stages of edible insects, per 100 grams of dry matter. Finally, Table 8 presents information about the anti-nutrient content of insect-based foods, expressed in milligrams per 100 grams. Table 9 shows the elemental composition of insect excrements and organic fertilizers. The distribution in Latin America, the Americas, and the Caribbean are given in all tables.

5 Potential uses of insects: tips for applications in Latin American

5.1 Food industry

Traditionally consumed in various Latin American countries, edible insects face potential barriers in Western countries, where they may be perceived as unsafe and unappetizing (Baiano, 2020; Kim et al., 2021; Van-Huis et al., 2021). Overcoming such biases is crucial for promoting insect-based economies in Latin America, emphasizing the significance of insect processing technologies (de Castro et al., 2018; Kim et al., 2021; Van-Huis et al., 2021). Given the rising global demand for protein, which is projected to grow by 9.1% from 2020 to 2027, and the necessity for sustainable protein sources in contrast to traditional livestock-based supply chains, insect processing technologies are anticipated to have a dominant role in the future (da Costa-Rocha et al., 2021; Van-Huis et al., 2021; Munialo et al., 2022). The global market for insect-based products is expected to grow significantly, from $406 million in 2018 to an estimated $1.18 billion in 2023 (Gkinali et al., 2022; Munialo et al., 2022). This trend represents a significant opportunity for Latin American countries to participate in the growing global market (Kouřimská and Adámková, 2016). In particular, several commercial brands such as Gricha®, Griyum®, In Insect Nutri-tion®, and CrickEx® offer a variety of insect-based food products produced in Mexican insect farms. These products are currently available online to Latin American consumers (Cordoba-Aguilar et al., 2023).

Recent research in the field of edible insects has embraced a biorefinery approach, aiming to maximize the value of the three main fractions obtained from insects: proteins, lipids, and chitin, as well as other valuable products derived from insect biomass within the same processing chain (Caligliani et al., 2018; da Costa-Rocha et al., 2021). New methodologies and techniques are essential for achieving optimal yields, quality, and functional properties of chemical compounds from insect biomass. The selection of techniques and processing steps directly impacts the quality, content, functional properties, palatability, and biosafety of insect extracts (de Castro et al., 2018; Ojha et al., 2021; Queiroz et al., 2023; Rahman et al., 2023). Various methods have been explored to achieve these goals, including nitrogen freeze-drying, vacuum drying, supercritical CO_2 extraction, ultrasound, electric pulse field, high hydrostatic pressure, and ohmic heating (Queiroz et al., 2023; Rahman et al., 2023). The development of new technologies for processing insect biomass is crucial for enhancing the technological and functional properties of insect proteins. These technologies aim to optimize solubility, water and oil retention capacity, emulsifying and foaming ability, and gelling capacity, while ensuring the safety and nutritional value of the products (Van-Huis et al., 2021). While the initial investment in new technologies is substantial, they have demonstrated their value in addressing the challenges of processing industrial insect biomass. These technologies have demonstrated the ability to preserve the essential bioactive properties of insect-derived molecules, reduce the allergenicity of insect proteins, and increase the stability of reaction products (Mintah et al., 2019; Ojha et al., 2021).

5.2 Agroindustries for animal husbandry

In agro-industrial applications, the black soldier fly (BSF) *Hermetia illucens* and other insect species, such as the house fly and *Tenebrio molitor* (TM), are widely used as valuable sources of meal for animal feed due to their high protein content (Hall et al., 2018; Sánchez et al., 2021). *Tenebrio molitor* larvae have also been utilized as animal feed because of their high protein and essential amino acid content. These larvae are rich in saturated, polyunsaturated, and monounsaturated fatty acids, as well as minerals, iron, and zinc making them a viable option for poultry feed. They have high nutrient availability for chickens and exhibit angiotensin-converting enzyme inhibitory activity, effectively stabilizing blood pressure (Dalmoro et al., 2021; Nascimento-Filho et al., 2021). Dietary treatments with BSF larvae and TM were found to beneficially reduce total blood cholesterol levels while increasing phosphorus levels in turkeys fed this protein source (Kozłowski et al., 2021). The meal derived from house fly larvae, with a protein content of 54% and a lipid content of 22%, is suitable for human consumption due to its favorable microbiological activity. It is rich in essential amino acids and unsaturated fatty acids, making it a promising source of protein for the diet of broiler chickens (Hall et al., 2018; Sánchez et al., 2021). Another case is the larval biomass of BSF contains 40% protein and 30% fat, making it suitable as a highly nutritious fish feed and a potential substitute for soy and maize in poultry diets

TABLE 2 Proximate nutrient composition of edible insects (g/100 g dry matter basis) and their distribution in Latin America and the Caribbean.

Insect	Distribution	DS	Protein	Fat	Fibre	NFE*	Ash	Reference
Blattodea (including infra-order Isoptera)								
Edible cockroaches and termites			46.3	31.3	5.2	13.7	4.4	Rumpold and Schlüter (2013)
Microtermes bellicosus	Not Found in America	A	40.7	44.8	5.3	2.2	5.0	Akullo et al. (2018)
Microtermes nigeriensis	Not Found in America	A	37.5	48.0	5.0	2.1	3.2	Omotoso (2015)
Odototermes sp.	Not Found in GBIF	A	33.7	50.9	6.3	6.1	3.0	Chakravorty et al. (2016)
Syntermes sp. soldier	Central America and South America	A	64.7	3.1	23.0	2.5	4.2	Akullo et al. (2018)
Coleoptera								
Edible beetles			40.7	33.4	10.7	13.2	5.1	Rumpold and Schlüter (2013)
Allomyrina dichotoma	Not Found in America	L	54.2	20.2	4.0	17.7	3.9	Ghosh et al. (2017)
Oryctes rhinoceros	USA Center and Mexico	L	52.0	10.8	17.9	2.0	11.8	Akullo et al. (2018)
Protaetia brevitarsis	Not Found in America	L	44.2	15.4	11.1	22.5	6.9	Ghosh et al. (2017)
Tenebrio molitor	North America (West Center and East Canada, USA, Mexico) Central America and South America	L	53.2	34.5	6.3	1.9	4.0	Ghosh et al. (2017)
T. molitor	North America (West Center and East Canada, USA, Mexico) Center America and South America	P	51.0	32.0	12.0			Adámková et al. (2017)
T. molitor	North America (West Center and East Canada, USA, Mexico) Central America and South America	L	52.0	31.0	13.0			Adámková et al. (2017)
Zophobas morio	South East USA and Caribbean	L	46.0	35.0	6.0			Adámková et al. (2017)
Diptera								
Edible flies			49.5	22.8	13.6	6.0	10.3	Rumpold and Schlüter (2013)
Caliphora vomitoria	Canada and USA	A	64.9	0.7	16.6	12.2	5.6	Bbosa et al. (2019)
Hermetia illucens	North America, Central America, South America and Caribbean	Pre P	44.3	31.9	5.1	3.4	8.7	Bbosa et al. (2019)
Hermetia illuscens	South America	L	39.0	32.6	12.4		14.6	Nyakeri et al. (2017)
Hemiptera								
Edible bugs			48.3	30.3	12.4	6.1	5.0	Rumpold and Schlüter (2013)
Aspongopus nepalensis	Not Found in GBIF	A	10.6	38.4	33.5	15.3	2.2	Chakravorty et al. (2011)

(Continued)

TABLE 2 (Continued)

Insect	Distribution	DS	Protein	Fat	Fibre	NFE*	Ash	Reference
Hymenoptera								
Edible ants, bees, wasps			46.5	25.1	5.7	20.3	3.5	Chakravorty et al. (2016)
Oecophylla smaragdina	Not Found in America	A	55.3	15	19.8	7.3	2.6	Rumpold and Schlüter (2013)
Lepidoptera								
Edible moth			45.4	27.7	6.6	18.8	4.5	Rumpold and Schlüter (2013)
Cirina butyrospermi	Not Found in America	L	62.7	14.5	5.0	12.6	5.1	Bbosa et al. (2019)
Odonata								
Edible dragonfly, damselfly			55.2	19.8	11.8	4.6	8.5	Chakravorty et al. (2014) and Akullo et al. (2018)
Orthoptera								
Edible grasshoppers, crickets, locusts			61.3	13.4	9.6	13.0	3.9	Rumpold and Schlüter (2013)
Acheta domesticus	North America	A	62.6	12.2	8.0	12.3	5.0	Bbosa et al. (2019)
Brachytrupes sp.	Not Found in America	A	65.4	11.8	13.3	2.5	4.9	Akullo et al. (2018)
Brachytrupes orientalis	Not Found in GBIF	A	65.7	6.3	8.8	15.2	4.3	Chakravorty et al. (2014)
Chondacris rosea	Not Found in GBIF	A	68.9	7.9	12.4	6.7	4.2	Chakravorty et al. (2014)
Gryllus assimilis	North America, South America and Caribbean	A	56	32	7.0			Adámková et al. (2017)
Gryllus bimaculatus	Not Found in America	A	58.3	11.9	9.5	10.6	9.7	Ghosh et al. (2017)
Ruspolia nitidula	Not Found in America	A	40.8	46.3	5.9	3.7	3.3	Bbosa et al. (2019)
Schistocerca piceifrons piceifrons	Mexico	A	80.3	6.2	12.6		3.4	Pérez-Ramírez et al. (2019)
Teleogryllus emma	Not Found in America	A	55.7	25.1	10.4	0.7	8.2	Ghosh et al. (2017)

*DS, developmental stage; L, larva; P, pupa; N, nymph; A, adult; B, brood; NFE, nitrogen-free extract (indicative of soluble carbohydrates).

(Park, 2016). Studies have shown that quail and broiler chickens fed BSF larvae have increased concentrations of amino acids and fatty acids in their meat composition (Cullere et al., 2016, 2018). BSF larvae are globally recognized as high-quality animal feed and have been deemed safe for human and animal consumption by the Food and Agriculture Organization of the United Nations (FAO) [Wang and Shelomi, 2017; Association of American Feed Control Officials (AAFCO), 2023].

In the global marketplace, BSF larvae have become a popular choice for various animals in the agricultural industry. They are available in a variety of forms and packaging options. Dehydrated BSF larvae are tightly sealed in high-density polyethylene packaging specifically designed for poultry and ornamental fish. In addition, fat-free cakes made from BSF larvae, packaged in the same sealed polyethylene, are designed for smaller animals such as pigs and rabbits. Live or dehydrated black soldier fly pupae are also available (Wanjiku, 2018; Cullere et al., 2019).

BSF larval cakes have a protein profile similar to soy, with elevated levels of essential amino acids, making them an excellent source of protein for high-protein food markets (Patterson et al., 2021). Furthermore, black soldier fly (BSF) larvae can be processed into a high-quality, protein-rich meal that can serve as a substitute for concentrated feed in poultry and ornamental fish. The flour is also used to make treats for exotic pets, wildlife rehabilitators, and urban farmers (Bußler et al., 2016; Queiroz et al., 2021). Due to the nutritional value of the larval protein, it is possible to replace up to 25% of fish meal and 38% of fish oil in balanced animal diets with BSF larvae, providing a sustainable alternative (Xiao et al., 2018). In addition to being globally accessible, these BSF larvae products are specifically designed for urban and rural communities involved in poultry and ornamental fish farming. Insect farming and promoting environmental education contribute to converting organic materials into valuable resources. During this process, larval or pre-pupal insect biomass is generated on a small to medium scale for direct consumption or processing into feed for poultry, fish, and pig farming. This approach promotes the adoption of sustainable agro-industrial production methods and encourages ecological innovation and the use of technological tools (Wu et al., 2022).

TABLE 3 A comparative account of the proximate nutrient content of different species belonging to the same genus (g/100 g dry matter basis) and their distribution in Latin America and the Caribbean.

Genus	Species	Distribution	DS*	Protein	Fat	Fibre	NFE *	Ash	Reference
Blattodea									
Microtermes	*bellicosus*	Not Found in America	A	20.4	28.2	2.7	43.3	2.9	Banjo et al. (2006)
	notalensis	Not Found in GBIF	A	22.1	22.5	2.2	42.8	1.9	Banjo et al. (2006)
	subhylanus	Not Found in America	A	39.3	44.8	6.4	1.9	7.6	Kinyuru et al. (2013)
	bellicosus	Not Found in America	A	39.7	47.0	6.2	2.4	4.7	Kinyuru et al. (2013)
Periplaneta	*americana*	North America, Central America, South America and Caribbean	L, A	65.6	28.2	3.0	0.8	2.5	Ramos-Elorduy et al. (2012)
	australasiae	North America (Canada, Southwestern USA North and Southeastern USA, Mexico, Central America, South America and Caribbean)	L, A	62.4	27.3	4.5	2.7	3.0	Ramos-Elorduy et al. (2012)
Pseudacanthotermes	*militaris*	Not Found in America	A	33.5	46.6	6.6	8.7	4.6	Kinyuru et al. (2013)
	spiniger	Not Found in America	A	37.5	47.3	7.2	0.7	7.2	Kinyuru et al. (2013)
Coleoptera									
Oryctes	*boas*	Not Found in America	L	26.0	1.5	3.4	38.5	1.5	Banjo et al. (2006)
	rhinoceros	Central USA and Mexico	L	42.3	0.6		27.7	12.7	Onyeike et al. (2005)
Hemiptera									
Edessa	*conspersa*	Not Found in GBIF	N, A	36.8	45.8	10.0	4.2	3.2	Ramos-Elorduy et al. (1998) and Rumpold and Schlüter (2013)
	montezumae	Not Found in GBIF	N, A	37.5	45.9	10.9	2.1	3.7	Ramos-Elorduy et al. (1998) and Rumpold and Schlüter (2013)
	petersii	Not Found in GBIF	N, A	37.0	42.0	18.0	1.0	2.0	Ramos-Elorduy et al. (1997)
	sp.	Center and Southeastern USA, Mexico, Central America, South America and Caribbean	N, A	33.0	54.0	11.0		1.0	Ramos-Elorduy et al. (1997)
Hymenoptera									
Atta	*mexicana*	Southwestern and South USA, Mexico, Central America and South America	A	46.0	39.0	11.0	0.0	4.0	Ramos-Elorduy et al. (1997)
	cephalotes	Mexico, Central America, South America and Caribbean	A	43.0	31.0	10.0	14.0	2.0	Ramos-Elorduy et al. (1997)
Brachygastra	*azteca*	Mexico	B	63.0	22.0	3.0	9.0	3.0	Ramos-Elorduy et al. (1997)
	mellifica	South USA and Mexico	B	53.0	30.0	3.0	11.0	3.0	Ramos-Elorduy et al. (1997)
Polybia	*parvulina*	South America	B	61.0	21.0	6.0	8.0	4.0	Ramos-Elorduy et al. (1997)
	occidentalis nigritella	Mexico, Central America and South America	B	61.0	28.0	2.0	11.0	3.0	Ramos-Elorduy et al. (1997)
	occidentalis bohemani	Mexico, Central America and South America	B	62.0	19.0	4.0	13.0	3.0	Ramos-Elorduy et al. (1997)
Lepidoptera									
Anaphe	*infracta*	Not Found in America	L	20.0	15.2	2.4	66.1	1.6	Banjo et al. (2006)
	recticulata	Not Found in America	L	23.0	10.2	3.1	64.6	2.5	Banjo et al. (2006)
	venata	Not found in America	L	25.7	23.2	2.3	55.6	3.2	Banjo et al. (2006)
	sp.	Not Found in America	L	18.9	18.6	1.7	46.8	4.1	Banjo et al. (2006)

(Continued)

TABLE 3 (Continued)

Genus	Species	Distribution	DS*	Protein	Fat	Fibre	NFE *	Ash	Reference
Orthoptera									
Sphenarium	*purpurascens*	Mexico	A	65.2	10.8	9.4	11.6	3.0	Ramos-Elorduy et al. (2012)
	mexrcanum	Mexico	A	62.1	10.8	4.1	22.6	0.3	Ramos-Elorduy et al. (2012)
	purpurascens	Mexico		56.0	11.0	9.0	21	3.0	Ramos-Elorduy et al. (1997)
	histrio	Mexico		77.0	4.0	12.0	4.0	2.0	Ramos-Elorduy et al. (1997)
	sp.	Mexico		68.0	12.0	11.0	5.0	5.0	Ramos-Elorduy et al. (1997)

DS, developmental stage.

5.3 Agricultural fertilizers and bioprotectans

Insect farming residues, such as frass (a mixture of insect excreta, exuvia, and undigested residues) and cadavers, can play a crucial role in developing a circular economy management strategy for both the food industry and agro-industrial applications. By utilizing these residues in sustainable agriculture, particularly as alternatives to chemical fertilizers and pesticides, additional income can be generated (Fielding et al., 2013; Chavez and Uchanski, 2021; Poveda, 2021). This approach holds particular significance for Latin American countries where agricultural practices often align with subsistence agriculture because the use of residual biomass from insect farming can reduce economic costs associated with acquiring chemical fertilizers. The research on using insect farming byproducts as organic fertilizers are still limited (Khan et al., 2016; Poveda et al., 2019; Beesigamukama et al., 2022; Wantulla et al., 2023), existing evidence indicates the potential impact of insect frass and cadaver deposition on soil nutrient cycling processes. Ecological studies have demonstrated that frass from certain herbivorous insects, rich in nitrogen and labile carbon, promotes microbial growth, accelerates organic matter decomposition, and affects carbon and nitrogen mineralization and immobilization. The nitrogen content in insect frass may vary among different species, emphasizing the need to evaluate frass quality across different insect species (Kagata and Ohgushi, 2012b).

Recent research has focused on assessing the elemental composition of insect-produced frass, including nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), manganese (Mn), zinc (Zn), and other elements. Comparative analyses reveal that frass from various insect species contains concentrations of essential macronutrients (N, P, K), secondary macronutrients (Mg, Ca, S), and micronutrients (Mn, Fe, Cu, Zn, B) comparable or even higher than those found in commonly used organic fertilizers in agriculture, such as manures, composts, and agricultural by-products. However, the elemental composition of frass from various insect species needs further exploration due to the wide range of variations in nutritional quality (Frost and Hunter, 2008; Hillstrom et al., 2010; Kagata and Ohgushi, 2011, 2012a,b; Fielding et al., 2013). The elemental composition of frass from various edible insects shows a balanced ratio of primary macronutrients (N:P:K) at 2:1:2. Different groups of insects, such as coleopterans and termites, exhibit nitrogen-enriched ratios (5,1:2), while orthopterans and dipterans display potassium-enriched ratios (6,1,15 and 1:1:3, respectively). Coleopterans and Lepidopterans exhibit nitrogen-to-potassium enriched ratios of 14:7 and 10:8, respectively. This variation in elemental composition is closely related to the diet of insects (Fielding et al., 2013; Zhang et al., 2014; Poveda et al., 2019). By managing the nutritional quality of the food given to insects in agricultural practices, it is possible to adjust the proportions of macronutrients in insect waste (frass) to meet specific requirements for fertilizer production (Poveda et al., 2019). While altering insect diets to enhance the quality of their excrement (frass) is a viable strategy, additional research is necessary to evaluate its feasibility. In addition, given that the nitrogen and phosphorus content of insect bodies is nearly ten times higher than that of insect frass, utilizing carcasses produced during insect farming offers another opportunity to achieve the desired adjustments in frass composition (Elser et al., 2000).

Insects like the black soldier fly larvae are commonly utilized for organic waste decomposition, as they serve as efficient decomposers and biological controllers of other fly species during their larval stage. Black soldier fly larvae can reduce organic waste by approximately 65 to 78%, producing a valuable material for composting and agricultural fertilization. This approach is proving to be more efficient than traditional composting and vermiculture, which require longer processing times. The resulting humus is of exceptional quality and serves as an environmentally friendly fertilizer for a variety of indoor and outdoor crops, such as those found in gardens, parks, golf courses, and sports fields (Erickson et al., 2004). Controlled trials on crops such as lettuce, Swiss chard, basil, tomato, onion, barley, and corn using black soldier fly (BSF) and mealworm wastes as fertilizers have shown positive effects on plant characteristics, including increased fresh and dry weight, height, basal stem width, and leaf number (Buenrostro et al., 2000; Singh and Kumari, 2019; Chavez and Uchanski, 2021).

In addition to serving as an organic fertilizer, insect frass also demonstrates bioprotective and biostimulant properties in agriculture. These properties are likely due to the microorganisms present in the frass, which stimulate beneficial soil microorganisms that enhance various plant responses. These responses include enhanced growth, increased tolerance to abiotic stresses, and activation of systemic defense mechanisms against natural pests. The microorganisms, referred to as plant growth-promoting microorganisms, play a crucial role in improving plant growth and productivity through various activities such as synthesizing hormones, solubilizing phosphate and

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TABLE 4 Amino acid composition of different species belonging to the same genus and their distribution in Latin America and the Caribbean.

Genus	Species	Distribution	Amino Acid Composition (% of Total Amino Acids or Protein)																		TAAP	Reference
			Val	Ile	Leu	Lys	Tyr	Thr	Phe	Trp	His	Met + Cys	Total EAA**	Arg	Asp	Ser	Glu	Gly	Ala	Pro		
Apis *(P)	*mellifera*	All America	5.9	5.6	8.0	7.0	5.0	5.0	1.0	ND	2.7	1.0	40.0	5.6	9.0	4.9	21.0	6.0	7.1	ND	41.0	Ghosh et al. (2016)
	ceranu	West and East USA	6.1	4.7	9.0	6.0	4.0	4.0	4.0	ND	2.5	4.7	45.0	4.9	12.0	4.7	10.0	7.0	9.6	6.6	51.0	Ghosh et al. (2020)
	dorsata	Not Found in America	5.7	4.4	9.0	6.0	3.0	4.0	4.0	ND	2.6	4.9	43.0	4.9	13.0	4.9	11.0	8.0	8.5	6.9	39.0	Ghosh et al. (2020)
	floren	Not Found in America	5.9	4.8	9.0	7.0	5.0	5.0	5.0	ND	2.8	4.8	48.0	5.3	10.0	5.1	14.0	6.0	8.1	7.6	36.0	Ghosh et al. (2020)
Bombus *(A)	*ignitus*	Not Found in America	7.0	5.7	9.0	6.0	3.0	2.0	3.0	ND	3.0	6.1	45.0	4.0	0.0	4.9	11.0	9.0	11.0	10.0	47.0	Ghosh et al. (2017)
	terrestris	Canada, USA and South America	6.3	5.0	8.0	8.0	3.0	2.0	3.0	ND	2.6	6.3	45.0	5.0	4.0	6.3	1.0	8.0	10.0	9.9	38.0	Ghosh et al. (2017)
Brachygastra (B)	*azteca*	Mexico	6.4	5.1	9.0	6.0	7.0	4.0	4.0	0.7	2.8	3.0	48.0	4.4	8.0	4.5	16.0	7.0	5.8	6.4	63.0	Ramos-Elorduy et al. (1997)
	mellifica	South USA and Mexico	5.4	4.4	8.0	4.0	8.0	4.0	4.0	0.7	3.6	3.8	45.0	5.7	9.0	4.2	16.0	7.0	6.1	7.1	53.0	Ramos-Elorduy et al. (1997)
Polybia (B)	*occidentalis nigratella*	Mexico, Central America and South America	5.9	4.5	8.0	7.0	6.0	4.0	3.0	0.7	3.0	5.0	47.0	5.7	8.0	4.5	13.0	7.0	6.5	6.3	61.0	Ramos-Elorduy et al. (1997)
	parvulina	South America	6.1	4.7	8.0	7.0	6.0	4.0	3.0	0.7	3.4	5.3	49.0	5.7	8.0	4.4	1.0	72.0	6.4	6.5	61.0	Ramos-Elorduy et al. (1997)
Polistes *	*sagittarius*	Not Found in America	6.6	5.5	8.0	4.0	5.0	4.0	5.0	ND	3.0	1.4	43.0	4.4	8.0	4.4	17.0	69.0	7.2	8.9	36.0	Ying et al. (2010)
	sulcatus	Not Found in America	67.0	6.2	8.0	4.0	5.0	4.0	4.0	ND	2.4	2.0	43.0	4.0	7.0	4.4	15.0	9.0	8.9	8.0	45.0	Ying et al. (2010)
Vespa * (B)	*velutina*	Not Found in America	6.1	5.5	9.0	6.0	7.0	4.0	4.0	ND	3.2	2.4	47.0	4.5	6.0	4.5	20.0	6.0	5.5	6.1	38.0	Ghosh et al. (2021)
	mandarinia	Canada	6.3	5.7	9.0	6.0	7.0	4.0	4.0	ND	3.3	27.0	49.0	2.2	7.0	4.3	21.0	6.0	5.4	5.7	37.0	Ghosh et al. (2021)
	basalis	Not Found in America	5.7	5.3	9.0	7.0	7.0	4.0	4.0	ND	3.2	1.4	47.0	4.3	6.0	4.3	22.0	6.0	5.0	5.7	28.0	Ghosh et al. (2021)
Vespa *(L)	*basalis*	Not Found in America	5.9	5.9	8.0	4.0	6.0	4.0	4.0	ND	2.5	2.1	43.0	3.9	8.0	4.3	17.0	8.0	7.7	8.4	44.0	Ying et al. (2010)
	mandarinia mandarinia	Not Found in America	5.0	4.6	6.0	17.0	4.0	3.0	11.0	ND	2.1	0.8	53.0	3.3	6.0	3.4	1.0	6.0	6.5	7.9	52.0	Ying et al. (2010)
	velutina auraria	Not Found in America	6.9	5.9	8.0	3.0	8.0	4.0	4.0	ND	3.1	2.9	45.0	6.3	9.0	6.5	12.0	8.0	7.1	5.9	49.0	Ying et al. (2010)
	tropica duenlis	Not Found in America	7.5	5.4	8.0	3.0	5.0	5.0	4.0	ND	1.4	1.2	41.0	7.1	10.0	5.0	13.0	9.0	7.8	6.6	42.0	Ying et al. (2010)
Sphenarium	*histrio*	Mexico	5.1	5.3	9.0	6.0	7.0	4.0	12.0	0.6	1.9	3.3	54.0	6.6	9.0	5.1	5.0	5.0	7.6	7.2	77.0	Ramos-Elorduy et al. (1997)
	purpurascens	Mexico	5.7	4.2	9.0	6.0	6.0	3.0	10.0	0.7	2.2	4.3	51.0	6.0	9.0	4.8	11.0	7.0	6.4	6.2	56.0	Ramos-Elorduy et al. (1997)

TAAP, Total Amino Acids or Protein (g/100 g Dry Matter); L, Larva; P, Pupa; A, Adult; B, Brood; ND, Not determined or not estimated; *Amino acid content was obtained from the respective paper and recalculated as g/100 g of total amino acids or protein (g/100 g dry matter) egg reference protein; **EAA, Essential amino acids, including (Val, Ile, Leu, Lys, Thr, Trp, Phe, His, Met) and two conditional essential amino acids (Tyr, Cys).

TABLE 5 Fatty acid composition of selected edible insects and their distribution in Latin America and the Caribbean.

Genus	Species	Distribution	DS	Fatty Acid Composition (% of Total Fatty Acids)								TFA	Reference
				C14:0	C16:0	C18:0	SFA	C18:1	MUFA	C18:2	PUFA		
Apis[+]	*cerana*	West and East USA	L	3.9	38.2	8.1	50.7	46.9	48.7	0.5	0.7	6.1	Ghosh et al. (2020)
			P	3	31.4	10.6	46.2	49.8	52.7	0.9	1.1	6.3	Ghosh et al. (2020)
			A	1.9	18.2	12.1	33.8	57.7	63.4	2.6	2.8	4.2	Ghosh et al. (2020)
	dorsata	Not Found in America	P	3.2	33.3	11.8	49.4	47.7	49.8	0.8	0.8	6.2	Ghosh et al. (2020)
			A	1	14.4	14.4	31.3	61	66.5	2.2	2.2	3.1	Ghosh et al. (2020)
	mellifera	All America	L	2.4	37.3	11.8	51.8	47.5	48.2	0	0	4.9	Ying et al. (2010)
			P	2.9	35.1	12.6	51.1	47.6	48.9	0	0	5.5	Ying et al. (2010)
			A	0.6	14.4	9.3	25.2	45.2	67	7.8	7.8	1.7	Ying et al. (2010)
	florea	Not Found in America	P	1.8	35.3	8.8	46.6	47.6	52.3	1	1.1	7.2	Ghosh et al. (2020)
			A	1.5	30.7	9.7	43.2	49.7	55.7	1.1	1.1	5.4	Ghosh et al. (2020)
Aspongopus	*viduatus*	Not Found in GBIF	A	0.3	31.3	3.5	37.9	45.5	56.8	4.9	5.4	54.2	Mariod et al. (2011)
	nepalensis	Not Found in GBIF	A	0.4	32.3	4.8	37.5	46.4	56.1	6.1	6.1	35.9	Chakravorty et al. (2011)
Bombus[*,+]	*ignitus*	Not Found in America	A	2.6	16.1	1.7	22.1	49.1	75.4	2.5	2.5	9.5	Ghosh et al. (2017)
	terrestres	Canada, USA and South America	A	3.8	15.2	1.7	21.5	51.1	76.2	2.2	2.2	8.4	Ghosh et al. (2017)
Imbrasia	*belina*	Not Found in GBIF	L	1.2	31.9	4.7	37.9	34.2	36	6	26.1	23.4	Ekop et al. (2009)
	epimethea	Not Found in America	L	0.6	23.2	22.1	46.1	8.4	9	7	42.5	13.3	Rumpold and Schlüter (2013)
	truncata	Not Found in America	L	0.2	24.6	21.7	46.5	7.6	7.6	7.6	44.4	16.4	Rumpold and Schlüter (2013)
	ertli	Not Found in America	L	1	22	0.4	61.4	2	24	20	31	11.1	Santos et al. (1976) and Bukkens (1997)
	oyemensis	Not Found in GBIF	L	0.5	46	7.2	54.2	34.6	34.6	11.2	11.2	25.4	Rumpold and Schlüter (2013)
Macrotermes	*bellicosus* **	Not Found in America	A	2.2	42.5	2.9	490	15.8	17.9	24.2	33.1	36.1	Ekop et al. (2009)
	bellicosus	Not Found in America	A	0.2	46.5		46.7	12.8	14.9	34.4	38.3	46.1	Rumpold and Schlüter (2013) and Ukhun and Osasona (1985)
	nigeriensis	Not Found in GBIF	A	0.6	31.4	7.1	39.4	52.5	53.1	7.6	7.6	34.2	Igwe et al. (2011)
	subhylinus	Not Found in America	A	1.1	27.7	6.3	35.1	48.6	52.8	10.8	12.2	44.8	Kinyuru et al. (2013)
	bellicosus	Not Found in America	A	1.2	38.4	9.5	49.5	41.7	44.6	5	5.9	47	Kinyuru et al. (2013)
Pseudacanthotermes	*militaris*	Not Found in America	A		26	5.9	32.2	50.3	56.1	11.5	11.7	46.6	Kinyuru et al. (2013)
	spiniger	Not Found in America	A	0.8	28	6.1	35.8	49.3	52.9	10.5	11.3	47.3	Kinyuru et al. (2013)
Oryctes	*owariensis*	Not Found in America	L	2.5	0.2	0.2	3.1	5.2	43.6	45.5	50.9	53.8	Womeni et al. (2009)
	rhinoceros	USA and Mexico	L	3.5	28.7	2.1	34.4	41.5	45.9	14.1	19.7	38.1	Ekop et al. (2009)
Vespa[+]	*velutina*	Not Found in America	B	6	31.9	7.8	48.3	35.3	39.7	5.2	12.1	11.6	Ghosh et al. (2021)
	mandarinia	Canada	B	2.5	21.3	5	30.7	27.7	29.2	33.7	40.1	20.2	Ghosh et al. (2021)
	basalis	Not Found in America	B	1.4	15.8	5.4	24.3	23.9	25.2	42.8	50.5	22.2	Ghosh et al. (2021)

DS, Developmental Stage; L, Larva; P, Pupa; A, Adult; [+]Fatty acid content (mg/100 g dry matter) was obtained from the respective paper and recalculated as % of total fatty acids; *Mated queen; **Oil. SFA, Saturated fatty acids; MUFA, Monounsaturated fatty acids; PUFA, Polyunsaturated fatty acids; TFA, Total Fatty Acids or Fat (g/100 g Dry Matter).

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TABLE 6 Minerals content of selected edible insects (mg/100 g) and their distribution in Latin America and the Caribbean.

Genus	Species	Distribution	DS	Ca	Mg	Na	K	P	Fe	Zn	Cu	Mn	Reference
Anaphe	*infracta*	Not Found in America	L	8.6	1.0			111.3	1.8				Banjo et al. (2006)
	reticulate	Not Found in America	L	10.5	2.6			102.4	2.2				Banjo et al. (2006)
	venata	Not Found in America	L	8.6	1.6			100.5	2.0				Banjo et al. (2006)
	sp.	Not Found in America	L	7.6	1.0			122.2	1.6				Banjo et al. (2006)
	venata	Not Found in America	L	40.0	50.0	30.0	1150.0	730.0	10.0	10.0	1.0	40.0	Ashiru (1989)
Apis	*cerana*	West and East USA	L	63.1	86.6	37.2	823.1	715.6	5.9	7.3	1.0	1.1	Ghosh et al. (2020)
			P	62.9	104.3	44.4	1153.2	931.5	7.1	7.7	1.2	0.2	Ghosh et al. (2020)
			A	91.1	148.8	77.1	1538.8	1283.9	11.1	12.9	1.9	0.2	Ghosh et al. (2020)
	dorsata	Not Found in America	P	68.9	103.4	48.6	1136.6	905.0	5.8	6.4	1.1	0.1	Ghosh et al. (2020)
			A	78.5	113.3	53.9	1254.3	972.3	7.6	7.4	1.2	0.1	Ghosh et al. (2020)
Brachytrupes	*orientalis*	Not Found in GBIF	A	76.3	87.2	112.0	412.3		18.7	8.5	1.5	5.0	Chakravorty et al. (2014)
	sp.	Not Found in America	A	9.2	0.1			126.9	0.7				Rumpold and Schlüter (2013)
Imbrasia	*epimetheus*	Not Found in America	L	224.7	402.2	75.3	1258.1	666.7	13.0	11.1	1.2	5.8	Rumpold and Schlüter (2013)
	ertli	Not Found in America	L	55.0	254.0	2418.0	1204.0	600.0	2.1		1.5	3.4	Rumpold and Schlüter (2013)
	oyemensis	Not Found in America	L	73.0		730.0	680.0						Rumpold and Schlüter (2013)
Macrotermes	*subhylanus*	Not Found in America	A	58.7					53.3	8.1			Kinyuru et al. (2013)
	bellicosus	Not Found in America	A	63.6					116.0	10.8			Kinyuru et al. (2013)
Pseudacanthotermes	*militaris*	Not Found in America	A	48.3					60.3	12.9			Kinyuru et al. (2013)
	spiniger	Not Found in America	A	42.9					64.8	7.1			Kinyuru et al. (2013)

DS, Developmental Stage; L, Larva; P, Pupa; A, Adult.

potassium, fixing nitrogen, and producing enzymes like glucanases, chitinases, and ACC (1-aminocyclopropane-1-carboxylate) deaminases, among others (Poveda et al., 2019; Barragán-Fonseca et al., 2022).

Tenebrio molitor frass was found to contain a diverse microbial community, including over 4,700 bacterial and 1,200 fungal strains, many of which were identified as plant growth-promoting microbes. The removal of these microbial strains from TM frass resulted in reduced plant growth and yield in fertilization experiments (Poveda et al., 2019). Studies have shown that using insect frass in fertilization experiments can activate plant defenses against pathogens and pests, leading to improved overall plant health. Root-colonizing microbes, such as beneficial rhizobacteria like *Bacillus, Pseudomonas*, and *Serratia*, can trigger systemic resistance in plants and bolster defense mechanisms against potential pathogen or insect attacks (Pineda et al., 2013; Ray et al., 2015, 2016; Chavez and Uchanski, 2021).

The bioprotective effect of insect frass on plants is attributed to specific chemical compounds, known as effectors or elicitors, present in the frass. Chitin and chitosan, derived from the exoskeletons of insects, are considered potent elicitors that mimic compounds to which plants respond when attacked by pathogens containing chitin. These compounds elicit various plant responses, including the

TABLE 7 A comparative account of the proximate nutrient content of different developmental stages of edible insects (g/100 g dry matter basis).

Insect	Distribution	DS*	Protein	Fat	Fibre	NFE +	Ash	Reference
Coleoptera								
Tenebrio molitor	North America and South America	L	47.7	37.7	5.0	7.1	3.0	Ramos-Elorduy et al. (2002)
		P	53.1	36.7	5.1	1.9	3.2	Ramos-Elorduy et al. (2002)
		A	60.2	20.8	16.3	0.0	2.7	Ramos-Elorduy et al. (2002)
Rhynchophorus phoenicis	Not Found in America	Early L	9.1	61.5	22.1	4.9	2.4	Omotoso and Adedire (2007)
		Late L	10.5	62.1	17.2	7.8	2.3	Omotoso and Adedire (2007)
		A	8.4	52.4	21.8	16.0	1.4	Omotoso and Adedire (2007)
Rhynchophorus phoenicis	Not Found in America	L	23.4	54.2	3.4	5.0	5.2	Opara et al. (2012)
		Immature P	33.1	42.7	3.1	6.7	7.4	Opara et al. (2012)
		Mature P	34.9	47.1	2.4	5.6	3.0	Opara et al. (2012)
		A	34.1	44.7	7.2	4.0	5.8	Opara et al. (2012)
Rhynchophorus phoenicis	Not Found in America	Early L	9.1	24.2	5.8	13.0	2.4	Chinweuba et al. (2011)
		Late L	10.5	25.4	6.0	12.0	2.3	Chinweuba et al. (2011)
Oryctes rhinoceros	USA and Mexico	L	70.8	7.5	5.4	7.0	8.3	Omotoso (2018)
		P	65.3	20.2	2.2	4.3	3.2	Omotoso (2018)
		A	74.2	9.6	3.7	2.8	5.3	Omotoso (2018)
Hymenoptera								
Apis mellifera	All America	L	42.0	19.0	1.0	35.0	3.0	Ramos-Elorduy et al. (1997)
		P	49.0	20.0	3.0	24.0	4.0	Ramos-Elorduy et al. (1997)
Apis mellifera ligustica	Not Found in America	L	35.3	14.5		45.1	4.1	Ghosh et al. (2016)
		P	45.9	16.0		34.3	3.8	Ghosh et al. (2016)
		A	51.0	6.9		30.5	11.5	Ghosh et al. (2016)
Orthoptera								
Acheta domesticus (as is basis)	North America (Canada, USA and Mexico)	N	15.4	3.3	5.8	0.9	1.1	Finke (2002)
		A	20.5	6.8		10.0	1.1	Finke (2002)
Zonocerus variegatus	Not Found in America	N1	18.3	4.3	0.9	0.4	1.9	Ademolu et al. (2010)
		N2	14.4	4.8	0.9	0.4	1.0	Ademolu et al. (2010)
		N3	16.8	2.9	1.5	0.9	0.9	Ademolu et al. (2010)
		N4	15.5	0.7	0.9	9.7	1.6	Ademolu et al. (2010)
		N5	14.6	1.1	0.9	9.8	1.6	Ademolu et al. (2010)
		N6	16.1	0.9	1.0	8.8	1.5	Ademolu et al. (2010)
		A	21.4	0.9	1.2	10.0	1.4	Ademolu et al. (2010)

*DS, Developmental Stage; L, Larva; P, Pupa; N, Nymph; A, Adult stage.

expression of defense-related genes, activation of jasmonate hormones, production of phytoalexins, phenolics, terpenes, and reactive oxygen species, and cellular changes such as cytoplasmic acidification, deposition of callose and lignin, and cell death (Sharp, 2013; Barragán-Fonseca et al., 2022). The positive effects of using frass on plant health emphasize its potential for controlling plant pathogens and pests. However, further studies are needed to determine the minimum effective dose of insect frass to stimulate plant defense responses and whether these responses vary among frass from different insect species (Poveda, 2021; Barragán-Fonseca et al., 2022; Lopes et al., 2022; Wantulla et al., 2023).

5.4 Pharmaceuticals

Insects are valuable sources of chemical compounds with significant pharmaceutical applications. Alloferons, which are peptides extracted from bacteria-infected *Calliphora vicina* fly maggots, such as alloferon-1, have been found to stimulate natural killer cell activity and interferon synthesis. They also exhibit antitumor and antiviral properties. Alloferon-1 has been implicated in regulating acute and chronic inflammatory responses in various diseases, such as skin and corneal epithelial cells, rheumatoid arthritis, and asthma (Ryu et al., 2008; Zhang et al., 2014; Jo et al., 2022; Lee et al., 2023).

TABLE 8 Antinutrient content in Insect-based Foods (mg/100 g) and their distribution in Latin America and the Caribbean.

Insect	Distribution	Phytate	Tannin	Oxalate	Trypsin Inhibitor	Lectin	Hydrocyanide	Reference
Ant +		2030.8	400.0					Adeduntan (2005)
Termite +		242.21	948.3					Adeduntan (2005)
Winged termite+		1128.2	250.0					Adeduntan (2005)
Cricket +		3159.0	900.0					Adeduntan (2005)
Meal bug		225.44	1150.0					Adeduntan (2005)
Grasshopper+		1100.1	1050.0					Adeduntan (2005)
Anaphe venata+	Not Found in America	1918.0	753.3					Adeduntan (2005)
Tree Hopper			1000.0					Adeduntan (2005)
*Rhynchophorus phoenicis**L	Not Found in America	1.4	1.0	0.1	0.9	0.6		Ekop et al. (2010)
Gymnogryllus lucens+ A	Not Found in GBIF	0.03	0.03	1.3			0.2	Ekop et al. (2010)
Heteroligus meles +	Not Found in America	0.03	0.04	0.3			0.3	Ekop et al. (2010)
Rhynchophorus + L	South Western and Eastern USA, Mexico, Central America, South America and Caribbean	0.03	0.04	1.8			0.2	Ekop et al. (2010)
Zonocerus variegatus+ A	Not Found in America	0.03	0.04	2.6			0.3	Ekop et al. (2010)
Oedaleus abruptus+ A	Not Found in America		2450.0	600.0				Ganguly et al. (2013)
*Lethocerus indicus** N, A	West USA		372.3					Shantibala et al. (2014)
*Laccotrephes maculatus** N, A	Not Found in America		350.4					Shantibala et al. (2014)
*Hydrophilus olivaceous** A	Not Found in America		52.9					Shantibala et al. (2014)
*Cybister fripunclactus** A	Not Found in GBIF		301.7					Shantibala et al. (2014)
Crocolhemes servillia * N	Not Found in GBIF		465.3					Shantibala et al. (2014)
Macrotermes nigeriensis+ A	Not Found in GBIF	15.2	0.6	103.0				Omotoso (2015)
Oryctes rhinoceros+ L	USA and Mexico	16.1	0.6	109.0				Omotoso (2015)
Oecophylla smaragdina + A	Not Found in GBIF	171.0	496.7					Chakravorty et al. (2016)
Odontotermes sp. + A	Central America	141.2	615.0					Chakravorty et al. (2016)
Oxya hyla hyla + A	Not Found in GBIF		2316.0	474.0				Ghosh et al. (2016)
Oryctes rhinoceros+ L	USA and Mexico	37.0	5.6	1.3				Finke (2002)
Oryctes rhinoceros + P	USA and Mexico	39.4	6.8	1.3				Finke (2002)
Oryctes rhinoceros + A	USA and Mexico	41,1	4.2	1.2				Finke (2002)

L, Larva; P, Pupa; N, Nymph; A, Adult; *Anti-nutrient content was estimated based on wet weight; +Anti-nutrient content was estimated based on dry weight.

TABLE 9 Elemental composition of insect frass and organic fertilizers.

Insects	C	N	P	K	S	Ca	Mg	Mn	Fe	Cu	Zn	B	References
Coleoptera (9 spp)	241–492	2.7–77.5	0.1–14.9	0.97–30.0	1.7–3.2	0.9–22.0	0.4–7.3	0.04–4.5	0.09–43.3	0.002–0.031	0.010–0.614	0.006–0.074	Beesigamukama et al. (2022), Chen and Forschler (2016), and Zhang et al. (2014)
Diptera (2 spp)	391–782	4.3–46.6	3.8–52.0	13–41	4.9–6.9	6.4–10.0	1.3–8.0	0.4	7.8	0.027	0.17	0.03	Beesigamukama et al. (2022)
Lepidoptera (3 spp)	441–490	21–38	1.8–2.0	14–17	1.7–3.0	20–34	2.5–3.6	0.1–0.2	0.9–1.8	0.004–0.009	0.014–0.016	0.035–0.12	Beesigamukama et al. (2022)
Orthoptera (5 spp)	403–427	9.5–29.0	1.4–14.5	22–35	2.8–4.3	13–30	4.9–5.4	0.3–0.4	3.18–4.38	0.018–0.030	0.12–0.21	0.02–0.03	Beesigamukama et al. (2022)
Termitidae (3spp)	472–528	2.2–7.0	0.1–0.5	0.3–0.9	–	3.0–5.2	0.5–2.1	0.12–0.15	0.08–0.13	0.002–0.007	0.4–0.1	0.006–0.017	Chen and Forschler (2016)
EIIF	391–496	24–29	13–14	21–40	3.2–6.9	4.0–10.0	5.1–5.7	0.17–0.41	0.44–7.80	0.013–0.027	0.10–0.17	0.006–0.033	Poveda et al. (2019) and Beesigamukama et al. (2022)
Organic fertilizers	–	5.0–73.8	1.2–17.3	3.6–24.6	1.0–2.4	17–29	3.0–17.0	0.1–12.0	1.2–3.6	0.1–1.3	0.1–0.3	0.07–0.20	Green (2022) and Islam et al. (2018)

EIIF, edible insects produced by insect farming. Elemental composition in expressed in g/kg.

Cantharidin, a toxic compound extracted from blister beetles such as *Mylabris phalerata* and *M. cichorii*, has demonstrated promising antitumor effects by inhibiting the proteins phosphatase 1 (PP1) and phosphatase 2A (PP2A). It has the potential to treat various cancers, including bladder, colon, pancreatic, liver, breast, oral, and leukemia (Naz et al., 2020). Melittin, a peptide extracted from bee venom, has been shown to possess antitumor properties. Comprising 26 amino acids, melittin induces the creation of pores in lipid membranes, resulting in cell disruption and potential antitumor effects. However, its clinical application is limited due to significant hemolytic activity (Wang et al., 2022). Sericin, produced by silkworm larvae, offers several health benefits due to its composition of 18 amino acids, including eight that are essential for human metabolic processes. It has therapeutic properties such as accelerating wound healing, reducing blood pressure, protecting the nervous system, exhibiting anti-tumor activity, controlling blood sugar, reducing wrinkles, providing anti-aging effects, and possessing antioxidant capacity (Kunz et al., 2016; Suryawanshi et al., 2020).

Insects significantly contribute to our understanding of bioactive compounds. Philanthotoxins from digger wasps are helping researchers understand ligand-gated ion channels. Solenopsin from fire ants inspires the synthesis of insecticidal compounds. Bee venom components, such as apamin and melittin, have specific effects on potassium channels and act as membrane-active peptides. The saliva toxins of assassin bugs interact with the voltage-gated calcium channels in their prey. Some beetles produce diamphotoxin and leptinotarsin, which are hemolytic peptide toxins traditionally used as arrow venom. Wasp venom contains mastoparan, a potent peptide toxin (Kachel et al., 2018; Biondi et al., 2022; Ye et al., 2023). The investigation of insects as sources of bioactive compounds is a continuing area of research.

6 Future directions and conclusions

Latin America's adoption of insect consumption not only surpasses that of the European market but also demonstrates a promising growth trajectory. Insects are deeply rooted in the region's culinary heritage, holding a unique position as a traditional and significant food source. Their popularity stems not only from their culinary appeal but also from their substantial nutritional content, making them a valuable asset in addressing food security challenges prevalent in many Latin American communities (Halloran et al., 2018). Despite the acknowledged benefits, widespread hesitancy persists, driven by aesthetic concerns regarding insect appearance. However, as global challenges such as population growth, limited agricultural space, and environmental degradation intensify, the need to explore alternative food sources becomes urgent (Klaus and Nakamura, 2021). Insects offer a sustainable solution, providing an opportunity to address these challenges while also supporting cultural preservation and economic development. Insects provide a rich source of essential nutrients, offering a promising avenue to combat malnutrition, especially in regions with limited access to diverse and nutrient-dense foods. To ensure the safety and quality of insect-derived products, it is imperative to prioritize the development of regulated insect farming practices over consuming wild-caught specimens, which may pose health risks (Van Huis, 2016; Imathiu, 2020; Aguilar-Toalá et al., 2022). The establishment of legislation is crucial to standardize production methods and uphold consumer confidence in insect-based foods.

The growing acceptance of consuming edible insects in Latin America presents a multifaceted opportunity that includes economic prosperity, cultural preservation, and geopolitical influence. Economically, the cultivation and utilization of insects offer the potential to create new industries and job opportunities, contributing to the region's socio-economic development. The low production costs and high nutritional value of insects position them as a lucrative commodity in both domestic and international markets, fostering economic growth and trade expansion. Integrating insects into Latin American culinary traditions not only preserves cultural heritage but also fosters a sense of identity and pride within communities. By embracing insect consumption, Latin America reaffirms its cultural richness and diversity while addressing pressing global challenges sustainably. From a geopolitical standpoint, the region's leadership in insect production and consumption grants it a strategic advantage, elevating its prominence in the global food trade arena. Effective utilization of this valuable resource has the potential to propel Latin America to the forefront of the emerging insect-based food industry, solidifying its position as a key player in shaping the future of sustainable food systems worldwide. Through strategic investment, innovation, and collaboration, Latin America can harness the full potential of edible insects, paving the way for a more resilient, fair, and sustainable food future.

For these reasons, it is necessary to carry out activities aimed at the proper conservation and use of this privileged resource, such as

- Implementing educational programs to dispel myths and misconceptions about insect consumption, working with communities at the local level to raise awareness of the nutritional benefits and cultural importance of edible insects. This could include workshops, cooking demonstrations, and information campaigns tailored to different demographic groups.
- We can also encourage culinary professionals to incorporate edible insects into traditional and contemporary dishes by supporting initiatives that showcase the versatility and deliciousness of insect-based cuisine through food festivals, cooking competitions, and culinary events. This can help increase consumer acceptance and demand.
- In addition, there is a need to collaborate with government authorities to establish clear rules and regulations for the production, processing, and sale of edible insects. This should focus on food safety regulations to ensure the quality and integrity of insect products.
- Provide resources for research projects aimed at improving the nutritional profile, taste, and texture of edible insects. Encourage collaboration between academia, industry, and agricultural stakeholders to drive innovation in insect-rearing techniques and product development.
- In addition, there is a need to facilitate access to resources, training, and infrastructure required to establish community insect farms. Emphasizing the socio-economic benefits of insect farming, such as income generation and food security, can encourage community participation.
- Facilitate access to insect-derived products by expanding distribution networks and increasing market visibility. Explore innovative packaging methods and marketing strategies that cater to various consumer preferences and food trends.
- Direct efforts should be made to foster collaboration with international partners, agencies, research institutions, and industry stakeholders to leverage expertise and resources. It is important to learn from success stories and adapt proven strategies to the unique context of Latin America.

Author contributions

CG-E: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AV-L: Writing – review & editing, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Data curation. NC-C: Investigation, Methodology, Resources, Supervision, Validation, Writing – review & editing. HG-O: Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing. CG-R: Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing. JR-V: Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing. MS-C: Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing. LS-C: Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing. BR-V: Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition. FA-B: Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing. PA-H: Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition.

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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.

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EDITED BY
Rakesh Bhardwaj,
Indian Council of Agricultural Research (ICAR), New Delhi, India

REVIEWED BY
Temin Payum,
Jawaharlal Nehru College, Pasighat, India
Hammylliende Talang,
The ICAR Research Complex for North Eastern Hill Region (ICAR RC NEH),
Umiam, India

*CORRESPONDENCE
Hema Kesa
✉ hemak@uj.ac.za
Alex D. Tchuenchieu Kamgain
✉ kamgaina@uj.ac.za

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Availability and accessibility of indigenous foods in Gauteng region, South Africa

Hema Kesa[1,2]*, Alex D. Tchuenchieu Kamgain[1,3]*, Mthokozisi Kwazi Zuma[2,4] and Xikombiso Mbhenyane[2]

[1]Food Evolution Research Laboratory, School of Tourism and Hospitality, University of Johannesburg, Johannesburg, South Africa, [2]Division of Human Nutrition, Department of Global Health, Faculty of Medicine and Health Science, University of Stellenbosch, Stellenbosch, South Africa, [3]Centre for Food, Food Security and Nutrition Research, Institute of Medical Research and Medicinal Plants Studies, Yaoundé, Cameroon, [4]Agricultural Research Council, Central Office, Smallholder Agricultural Development Unit, Pretoria, South Africa

While South Africa maintains national food security, food insecurity persists at the household level, with not all households having access to sufficient food. Proposals to address this include promoting the consumption of indigenous foods (IF). However, urbanization in the Gauteng region has sparked a nutrition transition, characterized by increased consumption of Western diets, resulting in rising rates of malnutrition and non-communicable diseases. This study sought to assess the availability and accessibility of indigenous foods in the region for residents. A quantitative cross-sectional research survey was conducted in the Gauteng region, involving 746 participants who provided insights into their ways of acquiring indigenous foods and rated their overall availability. Additionally, the survey gathered opinions on IF availability across different settings and collected suggestions for improving IF accessibility. Among a list of 18 South African indigenous foods, between 55.2 and 77.2% of participants did not know where they could be obtained. Acquisition through vendors, with a maximum of 14% of respondents, emerged as relatively more popular compared to food markets, spaza shops, supermarkets, and home gardens. The majority of surveyed participants (55%) perceived indigenous foods as unavailable in the region. Agreement rates for the availability of indigenous foods for sale or serving in various settings were 53.5% for supermarkets, 42% for schools, 44.2% for hospitals, and 37.5% for workplaces. Respondents suggested several strategies to enhance IF accessibility in the region, including marketing, home gardens, farms, supermarkets, education, elders, restaurants, and schools/universities. Overall, there is a need for increased education on the nutritional benefits of indigenous foods and the implementation of policies to improve their accessibility in urbanized provinces like Gauteng.

KEYWORDS
diet-related diseases, public health, indigenous foods, food consumption, Gauteng province

1 Introduction

As reported by STATS-SA (2019) and van den Berg and Walsh (2023), there has been a decline in the percentage of households and individuals who had limited access to food in South Africa during the last decades. Although the country is food secure at a national level, South Africa is still food insecure at the household level as not all households have access to adequate food. Almost 20% of South African households had inadequate or severely inadequate access to food in 2017 (STATS-SA, 2019). Just under a third (29.6%) of households that comprise more than three children reported that food access was inadequate. This proportion is almost twice the national average. The COVID-19 pandemic lockdowns have worsened the situation in South Africa (Manduna, 2023). As an example, the National Income Dynamics Study (NIDS) Coronavirus Rapid Mobile (CRAM) Wave 1 survey conducted in 2020 revealed that 47% of South Africans ran out of money to buy food at the beginning of the pandemic and 21% of participants reported that someone in the household went hungry (Wills et al., 2023).

The promotion of indigenous food consumption has been recommended as one of the solutions to this food insecurity matter. They are food crops that have their origin in South Africa. Added to these crops are those that were introduced into the country and are now recognised as naturalised or traditional crops (South African Department of Agriculture, Forestry and Fisheries, 2013). They are divided into three main categories: namely grains, vegetables, and fruits. They require low manipulation, are highly nutrient-dense, and generally resistant to drought and crop diseases as they are better adapted to thrive in their indigenous environments. Indigenous foods can be used as food substitutes for starch-enriched foods such as maize and rice, eaten as is or processed into jams or juices—to name but a few of their many uses (Agribook.digital, 2024). They are rich and inexpensive sources of proteins, carbohydrates, dietary fibre, minerals, and vitamins for millions of people in developed and LMIC countries and are some of the basic foods of the indigenous populations of Africa (Mbhenyane, 2017).

Indigenous foods contain phytochemicals that are linked to protection against the development of non-communicable diseases such as cancer, diabetes, and hypertension. Some of these indigenous foods have been chemically analysed and contain active compounds such as organic sulphur, hypoglycaemic alkaloids, flavonoids, phytosterin glycosides, and polyacetylenes (Mbhenyane et al., 2013). Takaidza (2023) described the nutritional and healthy values of each of the 18 South African official indigenous food. It comprises grain crops such as pearl millet, grain sorghum, cowpea, bambara groundnuts, and mungbean; vegetables including *Cleome gynandra*, *Amaranthus*, Blackjack (*Bidens Pilosa*), Jew's mallow, cassava, and yam (*Amadumbe*); and fruits such as marula (*Sclerocarya birrea*), red milkwood, mobola (*Parinari curatellifolia*) plum, wild medlar, *num-num*, and Kei apple. The health benefits of indigenous foods in this respect are less known or promoted. Budreviciute et al. (2020) assert that traditional food in most countries including South Africa, is healthier and could play a key role in the prevention and management of non-communicable diseases (NCDs). Unfortunately, this diet has been replaced by unhealthy processed food that is rich in sugars and fats, animal-source foods also known as "modern diet" which is among the main causes of NCDs (Olatona et al., 2018; De Araújo et al., 2021; Lane et al., 2021; Alamnia et al., 2023). In 2016, non-communicable diseases (NCDs) accounted for up to 51% of all deaths in South Africa (WHO-World Health Organization, 2018). Given this alarming prevalence, concerns arise regarding the availability and accessibility of indigenous foods in urban areas, which are most affected by nutritional transition. Consequently, this study sought to evaluate the perspectives of residents in the Gauteng region, the most urbanized area in South Africa, regarding these critical aspects.

2 Methodology

2.1 Study design

The study was carried out using a quantitative cross-sectional descriptive research survey. It was conducted in the Gauteng region which consists of the cities of Johannesburg, Pretoria, Ekurhuleni, Soweto, Krugersdorp, Benoni, Boksburg, Germiston, and Vereeniging and their surrounding metropolitan areas in the eastern part of the Witwatersrand region. It is a province that is largely urbanized and directly concerned with nutrition transition.

2.2 Sampling

Participants were randomly chosen from the Gauteng region. Inclusion criteria stipulated that participants must be at least 18 years old and have resided in Gauteng for a minimum of 2 years. The survey was conducted from August to November 2019 in the nine municipalities of the province. A total of 746 people participated in the study which is representative of the population. Indeed, the minimum calculated sample size was supposed to be 440. This was obtained using Slovin's formula and by considering that the 15.7 million people Gauteng residents minus 23.6% of children under 15 years considering Census 2011 data.

$$n = N / \left(1 + Ne^2\right) \text{people} = 11\,994\,800 / \left(1 + 11\,994\,800 \times 0.0025\right) = 399.99$$

The minimal sample size was therefore 400 plus 10% to accommodate attrition, accruing 440.

2.3 Data collection

The survey utilized a self-administered questionnaire to gather information. It included closed-ended questions aimed at collecting data on various aspects, such as the sociodemographic profile of participants, their ways to acquire indigenous food (IF) crops, their opinion on how available indigenous foods is, and their interest to see IF availability and accessibility enhanced. Sociodemographic inquiries encompassed gender, race, age, education level, household size, monthly income, residential area, and corresponding settlement. Respondents were prompted to indicate how they acquire each listed IF (options included "Food markets," "Spaza shops," "Supermarket," "Grow in garden," "Vendors," or "Do not know"). They also expressed their overall perception of indigenous food availability by selecting from options like "Very poor," "Poor," "Average," "Good," or "Excellent." Furthermore, their opinions on IF being sold or served in schools, hospitals, supermarkets, and workplaces were gauged using responses like "yes," "maybe," or "no." Finally, respondents were invited to provide suggestions on enhancing IF accessibility in the region through an open-ended question "How can indigenous foods be made more accessible to Gauteng residents?"

The questionnaire was written in English, and a pilot study conducted on a diverse group of participants consisting of 15 people from different areas in Gauteng was completed to assess its validity and reliability. Field workers recruited for the study were able to communicate in all the official languages of South Africa. This was helpful to ensure that the questionnaire was correctly completed. Data collection took place in public venues such as malls, churches, and community centres across the six municipalities and three metropolitan areas in Gauteng.

2.4 Ethical consideration

This study was carried out under the ethics clearance numbers 2019STH012 and X20/11/040 of the University of Johannesburg and Stellenbosch University, respectively. Informed consent was obtained from each participant after the objectives of the study had been explained. Privacy and confidentiality were thoroughly maintained.

2.5 Data analysis

The collected data underwent analysis using Statistical Package for Social Sciences (SPSS) version 27 (IBM SPSS Statistics, Chicago, IL, United States). Descriptive analysis was conducted for closed-ended questions, while thematic analysis was employed for open-ended questions.

3 Results

3.1 Sociodemographic characteristics of the studied population

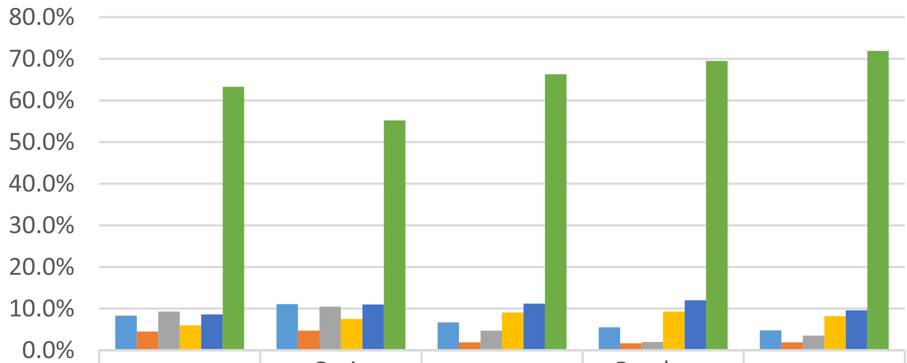
Table 1 illustrates the participant characteristics (n = 746). The cohort comprised females (59.8%) and males (40.1%), with the majority falling within the 18–55 age bracket (93%) and representing various racial groups as classified by South Africa (Black, Coloured, Indian, White), with Asians constituting a minority. Educational attainment was predominantly at either secondary (35.8%) or tertiary (61.9%) levels, and participants were primarily located in urban (65.8%) and peri-urban areas (24.8%). The housing types varied from single to family dwellings, and monthly incomes spanned a range from low to high. For international conversion, the exchange rate was ZAR 1 = EUR 0.049 = USD 0.054.

3.2 Ways to acquire indigenous foods

Figures 1–3 depict the different ways of obtaining indigenous grain crops, vegetables, and fruits. Participants were allowed to choose more than one way to acquire indigenous foods which were food markets, *spaza* shops, supermarkets, home gardens, and vendors, and were given the choice to choose "Do not know."

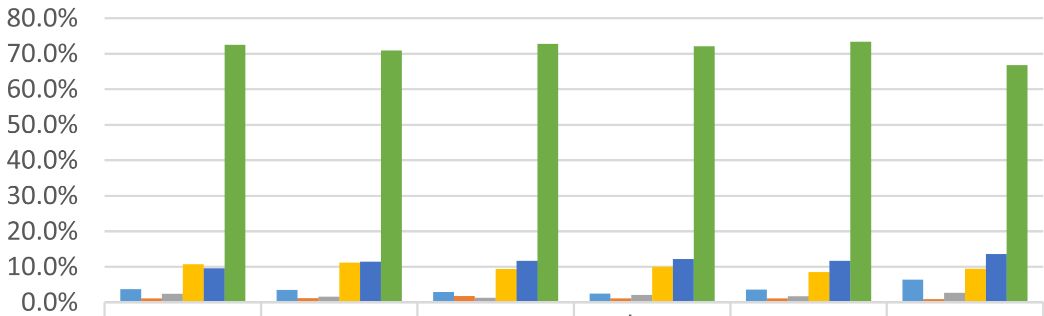
TABLE 1 Demographic profile of participants (N=746).

Demographic variables		Frequency (N)	Percentage (%)
Gender	Male	299	40.1
	Female	447	59.9
Race	Black	206	27.6
	Coloured	152	20.4
	Indian	142	19
	White	223	29.9
	Asian	21	2.8
	Other	2	0.3
Age group	18–25	207	27.7
	26–35	215	28.8
	36–45	171	22.9
	46–55	101	13.5
	56–65	37	5
	66+	14	1.9
	Missing	1	0.1
Highest education level	Grade 0–7	17	2.3
	Grade 8–12	267	35.8
	Tertiary Education	462	61.9
Household size	1–2	145	19.4
	3–5	441	59.1
	6 or more	160	21.4
Household income per month after tax	Less than R500	16	2.1
	R500–R999	13	1.7
	R1,000–R1,999	20	2.7
	R2,000–R2,999	39	5.2
	R3,000–R4,999	84	11.3
	R5,000–R9,999	94	12.6
	R10,000–R14,999	123	16.5
	R15,000–R24,999	117	15.7
	R25,000–R34,999	82	11
	R35,000–R44,999	67	9
	R45 000–R54 999	47	6.3
	R55 000+	44	5.9
Area of residence	Urban	491	65.8
	Peri-urban	185	24.8
	Rural	69	9.2
	Missing	1	0.1
Corresponding settlement of urban/peri-urban area	Informal settlement	60	8
	Former border or homeland towns	11	1.5
	Township (Kasi)	189	25.3
	Suburb / Edge city	416	55.8
	Missing	70	9.4



	Pearl millet	Grain sorghum	Cowpea	Bambara groundnuts	Mungbean
Food markets	8.3%	11.1%	6.7%	5.5%	4.8%
Spaza shops	4.5%	4.7%	1.9%	1.7%	1.9%
Supermarket	9.3%	10.5%	4.7%	2.0%	3.5%
Grow in gardens	6.0%	7.5%	9.1%	9.3%	8.2%
Vendors	8.6%	11.0%	11.2%	12.0%	9.6%
Do not know	63.3%	55.2%	66.3%	69.5%	71.9%

FIGURE 1
Ways in which indigenous grain crops are acquired. Gauteng province, South Africa, 2019.

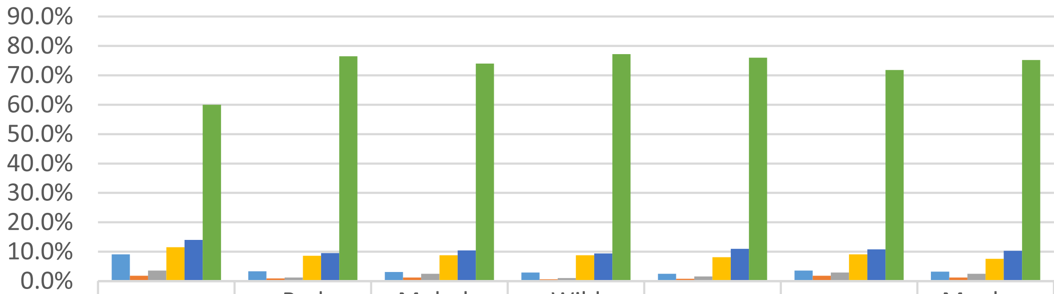


	Cleome	Amaranth	Blackjack	Jews mallow	Cassava	Amadumbe
Food markets	3.7%	3.5%	2.9%	2.5%	3.6%	6.4%
Spaza shops	1.1%	1.2%	1.8%	1.1%	1.1%	0.9%
Supermarket	2.4%	1.6%	1.3%	2.1%	1.7%	2.7%
Grow in gardens	10.7%	11.2%	9.4%	10.0%	8.5%	9.5%
Vendors	9.6%	11.5%	11.7%	12.2%	11.7%	13.6%
Do not know	72.5%	70.9%	72.8%	72.1%	73.4%	66.8%

FIGURE 2
Ways in which indigenous vegetable crops are acquired. Gauteng province, South Africa, 2019.

According to Figure 1, most participants were unaware of where to acquire various indigenous grain crops, including pearl millet (63.3%), grain sorghum (55.2%), cowpea (66.3%), bambara groundnuts (69.5%), and Mungbean (71.9%). Only a minority reported obtaining these crops from sources such as food markets, spaza shops, supermarkets, home gardens, and vendors. Among these, acquisition through vendors was relatively more common, yet overall accessibility to indigenous food crops was limited.

A similar pattern emerged concerning indigenous vegetable crops, as depicted in Figure 2. The majority of respondents [72.5% for



	Marula	Red milkwood	Mobola plum	Wild medlar	Num_num	Kei apple	Monkey orange
Food markets	9.1%	3.3%	3.1%	2.9%	2.5%	3.6%	3.2%
Spaza shops	1.8%	0.9%	1.2%	0.6%	0.8%	1.8%	1.2%
Supermarket	3.6%	1.2%	2.5%	1.0%	1.6%	2.9%	2.5%
Grow in gardens	11.5%	8.6%	8.8%	8.8%	8.1%	9.1%	7.6%
Vendors	14.0%	9.5%	10.4%	9.4%	11.0%	10.8%	10.3%
Do not know	60.0%	76.5%	74.0%	77.2%	76.0%	71.8%	75.2%

FIGURE 3
Ways in which indigenous fruits are acquired. Gauteng province, South Africa, 2019.

Cleome gynandra, 70.9% for *Amaranthus*, 72.8% for Blackjack (*Bidens Pilosa*), 72.1% for Jew's mallow, 73.4% for cassava, and 66.8% for yam (*Amadumbe*)] were uncertain about where to acquire them. Some participants did manage to obtain these indigenous vegetables from various sources such as food markets, spaza shops, supermarkets, home gardens, and vendors. Vendors were notably more popular, yet a minority of participants (11.2% for *Amaranthus*, 10.7% for *Cleome gynandra*, 10.0% for Jew's mallow, 9.4% for Blackjack, and 8.5% for cassava) reported growing these vegetables in their gardens. Despite some availability, indigenous vegetable crops remained relatively inaccessible to the participants.

Regarding indigenous fruits (as shown in Figure 3), the proportion of participants who were unsure of where to obtain them ranged from 60 to 77.2%. Specifically, uncertainty levels were 60.0% for marula (*Sclerocarya birrea*), 76.5% for red milkwood, 74.0% for mobola (*Parinari curatellifolia*) plum, 77.2% for wild medlar, 76.0% for *num-num*, and 71.8% for Kei apple. Only a small number of respondents mentioned acquiring these fruits from various sources such as food markets, spaza shops, supermarkets, home gardens, and vendors, with vendors being the preferred choice. Marula appeared as the most commonly cultivated fruit in participants' gardens (11.5%). Despite the possibility of obtaining some indigenous fruits, they were generally not easily accessible to the participants.

In evaluating the availability of indigenous foods (as shown in Figure 4), 32% of participants ($n = 235$) rated it as average, 31% ($n = 231$) as poor, 24% ($n = 180$) as very poor, 9% ($n = 70$) as good, and 4% ($n = 30$) as excellent. These findings indicate that participants generally did not perceive indigenous foods to be easily accessible or readily available.

As shown by Figure 5, a larger percentage of respondents expressed agreement with the idea of indigenous foods being available for sale or served in various settings such as schools, hospitals, supermarkets, and workplaces. Specifically, agreement rates were 53.5% for supermarkets ($n = 399$), 42% for schools ($n = 320$), 44.2% for hospitals ($n = 330$), and 37.5% for workplaces ($n = 280$). A portion of participants remained uncertain, responding with "maybe" (31.5–37.8%). Conversely, a minority disagreed with the notion of indigenous foods being sold or served in schools (23.9%, $n = 178$), hospitals (20.9%, $n = 156$), supermarkets (15.0%, $n = 112$), and workplaces (24.7%, $n = 184$). These findings suggest that participants generally desire increased accessibility and availability of indigenous foods for purchase and consumption.

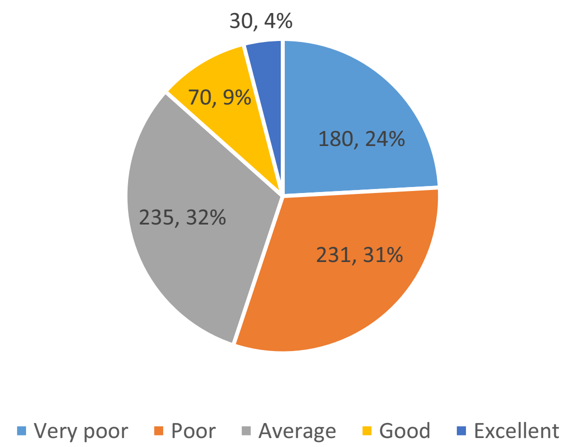


FIGURE 4
Participants' opinions on the level of availability of indigenous foods. Gauteng province, South Africa, 2019.

Table 2 displays the insights provided by participants regarding possible strategies to enhance the accessibility of indigenous foods for Gauteng residents. The following nine themes were established: marketing; home gardens; farms and land; supermarkets including grocery stores/local shops, street vendors/food markets; retailers; education and awareness; elders; restaurants offering indigenous foods; and schools and universities.

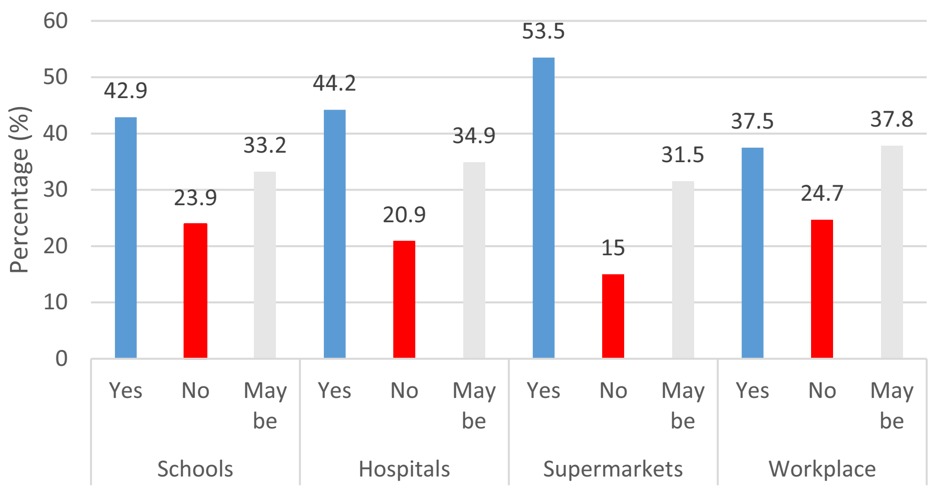


FIGURE 5
Participants' views on how the availability of indigenous foods could be increased. Gauteng province, South Africa, 2019.

4 Discussion

This study reveals that a significant portion of Gauteng residents lacked knowledge about where to acquire indigenous grain crops. Within the surveyed population, Black individuals exhibited greater familiarity with and consumption of indigenous foods compared to individuals from other racial groups, likely influenced by cultural factors (Kesa et al., 2023). Participants sourced indigenous grain crops from various outlets such as food markets, spaza shops, supermarkets, home gardens, and vendors, emphasizing the significance of supply-side factors in the indigenous foods discourse. Informal markets play a crucial role in the distribution of indigenous foods, as observed in the Tshakhuma and Khumbe markets in Limpopo province, where a substantial portion of trading revolves around indigenous foods (Nesamvuni et al., 2005). However, formal food markets in South Africa typically overlook indigenous foods, limiting access for informal traders. Smallholder farmers, who are major producers of indigenous foods, often market their produce through fresh produce markets, informal markets, and supermarket chains. Efforts to enhance integration with large fresh produce markets, such as the Johannesburg Fresh Produce Market (JFPM), are underway, including initiatives like building decentralised packing houses and grading point facilities to reduce transport costs and improve product quality (Aliber and Hart, 2009; Baiphethi and Jacobs, 2009; Jennings et al., 2015; Gutierrez et al., 2023).

Some of the participants cultivated indigenous crops in their gardens. It is often presented that in poorer countries urban food production is usually a survivalist or subsistence strategy but in more developed and affluent countries it acquires more recreational, health, or social undertones (Taylor and Lovell, 2012; Battersby and Marshak, 2013; Eigenbrod and Gruda, 2015). In the context of Gauteng, it is postulated that those who produced their indigenous foods in their gardens did so for sustenance and to ensure availability. Although some indigenous fruits could be obtained, they were not very accessible to the participants. A similar trend was noted in a study conducted by Matenge (2011) in the Northwest province in South Africa: urban communities mainly sourced their indigenous foods from informal markets, home gardens, and rural communities.

Data from the General Household Survey of 2018 by STATS SA indicated low levels of agricultural engagement among South African households, particularly in urban areas like Gauteng (Official Guide to South Africa, 2019). Participants did not find indigenous foods easily available or accessible in Gauteng. When asked where they would like to see indigenous foods become more available and accessible, the participants globally agreed to indigenous foods being sold or served in schools, hospitals, supermarkets, and workplaces. However, 31.5 to 37.8% of respondents reported "Maybe." This represents a high percentage. As noticed in a previous paper (Kesa et al., 2023), this surveyed urban population had a weak knowledge and consumption of indigenous foods. Akinola et al. (2020) had already pointed out the fact that people in Africa do not value indigenous foods and their potential benefits are thus neglected. Their awareness of the nutritional and health values of those indigenous foods can therefore be questioned. Despite this, there is a growing consensus among the studied participants for indigenous foods to be made more available and accessible, particularly in settings such as schools, hospitals, supermarkets, and workplaces.

As also suggest by respondents, addressing this demand requires a multifaceted approach, encompassing marketing strategies, promoting home gardens and farms, enhancing education and awareness, and engaging various stakeholders like elders, retailers, and restaurants (Shackleton et al., 2009). Urban agriculture presents an opportunity to mitigate malnutrition and food insecurity, utilizing vacant spaces in cities and peri-urban areas for agriculture (Eigenbrod and Gruda, 2015). Moreover, the production and incorporation of indigenous vegetables into the food chain hold economic promise for reducing poverty and unemployment, particularly in developing countries (Schreinemachers et al., 2018). Nutrition education is essential to promote the consumption of indigenous foods across all household members, including as complementary foods (Mushaphi et al., 2017).

Expanding the scope of research to include rural and peri-urban areas is essential for a comprehensive understanding, as the current survey predominantly focused on urban areas where individuals from various regions converge for shopping and entertainment.

TABLE 2 Responses on how indigenous foods can be more accessible in Gauteng (n=746).

Theme	Responses (verbatim)	Researchers' interpretation
Marketing (Advertising/ Branding/Price)	*There should be public promotions about indigenous foods.* *Online Mix cultures Food shows* *Advertise more and offer deliveries.* *Higher availability in mainstream stores as well as for marketing (e.g., featured in cooking shows, in-store recipes, local recipe books or web pages) would help create awareness.* *Indigenous foods must be branded and made available in food market with reasonable prices.*	In order to increase the consumption, of indigenous foods, it needs to be marketed to consumers. Participants provided examples of marketing, i.e., food shows, promotions, branding, recipe books (food preparation). The general public/consumers must be made aware of the benefits of indigenous foods.
Home gardens	*We should grow them in our gardens.* *We should be thought how to grow them.* *Self-gardening, vending distribution.* *Residents should grow them.* *Must be grown more in informal or even formal areas.*	Participants are receptive to indigenous crops being grown in their own gardens. To do that, they need to be trained/ educated. Home gardens (indigenous crops) should be encouraged in urban and rural areas.
Farms/land	*Farmers must produce more indigenous food.* *If farmers can produce more of it and transport them to Supermarkets in cities (JHB) then the residents could have access to the foods.* *By supplying land for people to promote the availability of plants.* *By giving people land to plough.* *Offer land to plant.* *Space to plant.* *Allocate land and opportunity to grow in JHB.* *Farmers around Johannesburg should start farming indigenous food.* *Johannesburg municipality can even promote and plant more of the same indigenous foods.*	More land needs to be made available for the growth of indigenous crops. Farmers need to be educated on how to grow and harvest indigenous crops. Urban farming i.e., in Johannesburg is also encouraged.
Supermarkets, grocery stores, local shops, street vendors, food markets	*Arrange to sell them at local Supermarkets.* *By bringing them from the farms into Supermarket areas. This practice is already done but there is more demand.* *Grocery stores, Vendors, fruit shop & veg shops.* *Make it more available in supermarkets in order for us to reach out to them.* *Very healthy but they sell in Supermarket's people know about it they will definitely buy it.* *Supermarkets, home grown, Vendors.* *Supermarket should promote them more than western foods.* *I believe by making indigenous foods more available in such stores would make indigenous foods more readily accessible.* *Many of us south Africans are not educated on these indigenous foods and if these foods can be sold at Supermarkets or grocery stores or even get Vendors to sell them to us at our doorsteps.* *Selling them on the street corners* *Be made available in Food market.* *Food market in Johannesburg* *It should be made readily available in Food market.*	The majority of the participants who completed the question, responded that indigenous foods could be sold in all supermarkets (formal and informal). This will ensure the availability and accessibility of indigenous foods and will encourage consumption. Other suggestions were vendors, local stores and food markets (in urban and rural areas)
Retailes: Spar, Woolworths, Shoprite, Pick n Pay, etc.	*Put indigenous food in markets like Shoprite.* *Through retail saturation on shelves* *Sell at speciality stores – fruit & veg shops – pharmacies (Dischem and others.).* *Indigenous foods can be made accessible to residents in Johannesburg. They should be marketed and sold at Supermarkets like Shoprite, pick-`-pay and Woolworths.* *They are available at food lovers' markets with instructions on how to cook and enjoy them.* *Being more available in Spar retail shops*	Retailers need to source indigenous foods and it should be sold in "big" supermarkets such as Spar, Woolworths, Shoprite and Pick n Pay. This will allow for increase availability and accessibility of indigenous foods.

(Continued)

TABLE 2 (Continued)

Theme	Responses (verbatim)	Researchers' interpretation
Education and awareness	*Be made more aware of the different types that are produced.* *By educating people.* *Educate more people about indigenous foods.* *Educate people and show them how to cook it.* *Educate people more on these foods and their benefits.* *Educate the middle class on indigenous foods.* *More awareness & information about these foods,* *Teach us how and where to grow them.* *Teach people about its nutritional value.* *Knowledge first – market them to people.* *Workshops on where, when and how to grow them.* *Having workshops in schools and community centres; have shops in malls.*	Consumers want to be educated on how to obtain indigenous crops/seeds, when to grow it, how to grow it and the nutritional benefits. Workshops should be offered by the agricultural department to urban, peri-urban and rural communities.
Elders	*By elders.* *If elderly people can pass on the knowledge to the youth about indigenous food, and the youth market it.*	Indigenous knowledge is very important and if passed on from generation to generation, there will always be an awareness. Elders play a big role in knowledge about indigenous foods (growth, harvesting and preparation of indigenous foods) and it is important for them to pass their knowledge onto the youth in order to encourage them about the benefits.
Restaurants offering indigenous foods	*Create more restaurants that sells these kinds of foods.* *Someone must open an African restaurant where they will sell indigenous foods only.*	More restaurants selling indigenous foods should be opened, incorporating indigenous foods into their menus.
Schools and universities	*Sell them at schools and universities.* *Sold at schools.* *Sell them at university.* *Educate school about indigenous foods.*	If they're sold at schools and universities, the youth can get more exposed to these foods. Schools can grow indigenous crops in their gardens and the crops can be incorporated in the school menus.

Gauteng province, South Africa, 2019.

5 Conclusion

Accessing various indigenous foods in the Gauteng Region poses significant challenges for the population. It is imperative to undertake efforts to enhance their availability and accessibility, especially considering the residents' willingness to consume them more frequently.

Data availability statement

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

Ethics statement

This study was carried out under the ethics clearance numbers 2019STH012 and X20/11/040 of the University of Johannesburg and Stellenbosch University, respectively. Informed consent was obtained from each participant after the objectives of the study had been explained. Privacy and confidentiality were thoroughly maintained.

Author contributions

HK: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. AT: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. MZ: Writing – review & editing. XM: Supervision, Writing – review & editing.

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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.

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EDITED BY
Amar Razzaq,
Huanggang Normal University, China

REVIEWED BY
Muhammad Aamir Shahzad,
Hunan University, China
Shamsheer Ul Haq,
University of Education Lahore, Pakistan
Muhammad Haseeb Raza,
Muhammad Nawaz Shareef University of Agriculture, Pakistan

*CORRESPONDENCE
Guangcheng Ma
mgc@163.sufe.edu.cn

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

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Consumer behavior and healthy food consumption: quasi-natural experimental evidence from Chinese household participation in long-term care insurance

Wenting Chen[1†], Guangcheng Ma[2*†] and Zhe Jia[3]

[1]College of Urban and Environmental Science, Northwest University, Xi'an, China, [2]School of Urban and Regional Sciences, Shanghai University of Finance and Economics, Shanghai, China, [3]School of Marxism, Xi'an University of Science and Technology, Xi'an, China

Introduction: There is a strong link between consumer behavior and healthy food consumption. However, how to narrow the gap between consumption intentions and actual healthy food consumption is still under discussion.

Methods: This study takes Chinese families as the research object, based on the family participation in long-term care insurance (LTCI) policy, and constructs an analytical framework including healthy eating behavior, food consumption, and insurance system to discuss how to narrow the gap between consumption intention and actual healthy food consumption. In addition, the intermediary role played by the risk prevention mechanism is also analyzed. Based on data from the China Health and Nutrition Survey (CHNS), this study uses a difference-in-differences analysis framework to empirically examine the impact of changes in consumption behavior on healthy food consumption after households participate in the LTCI pilot.

Results and discussion: The research results show that implementing LTCI can increase the frequency of healthy meal preparation methods by 0.045 units and the frequency of not including processed foods in the meals of households participating in the policy by 0.033 units compared with households that do not participate. The daily meal quantity is increased by 0.198 (converted to 1.219 grams), and 0.198 units increase the healthy food consumption structure. This conclusion holds under a series of robustness tests. Mechanism test shows that LTCI affects healthy food consumption through risk prevention mechanisms. The impact of the LTCI policy will also not be affected by similar competitive policies. The heterogeneity test further proves that LTCI policies are more likely to increase healthy food consumption among urban households, larger households, and households employed in private enterprises. Based on these findings, it is recommended that families participate in LTCI to reduce the financial stress faced by families due to illness and care needs while increasing the demand for and consumption of healthy foods. The findings also provide a valuable reference for current policy formulation on improving family dietary quality in China.

KEYWORDS

consumer behavior, healthy food consumption, long-term care insurance, Chinese families, dietary quality, quasi-natural experiment

1 Introduction

Healthy food consumption has emerged as a significant trend in contemporary society, reflecting people's pursuit of health and longevity. It is crucial for maintaining a healthy lifestyle (Luo et al., 2021; Kennedy et al., 2023). The vulnerability of food systems cannot curb malnutrition and stunting in children, making it more difficult for people to pursue healthy food (Haq et al., 2023). Currently, unhealthy dietary habits are closely linked to chronic conditions such as heart disease, hypertension, diabetes, and increased mortality (Solbak et al., 2017). The Interpretation of Report on Cardiovascular Health and Diseases in China 2022 notes that cardiovascular diseases such as hypertension and diabetes have become the leading cause of death for both urban and rural residents in China, with 48% in rural and 45.86% in urban areas. It seriously affects people's health status and has become a significant public health problem (Liu Y. et al., 2021). Furthermore, the dietary structure of most Chinese individuals does not align with the recommended Chinese food pyramid structure (Xu et al., 2015). Food consumption patterns of households are determined by their socio-economic status. Underconsumption of healthy foods is a severe problem for policymakers and nutritionists worldwide, especially in developing countries (Lian et al., 2023). Therefore, enhancing the structure of healthy food consumption presents a critical challenge in China. Likewise, as a good starting point for developing sustainable lifestyles, it is increasingly attracting global attention, and growing evidence highlights the actual and potential value of healthy food consumption in improving public health and promoting food security.

A close interconnection and mutual influence exists between consumer behavior and healthy food consumption (Eyinade et al., 2021). As public health awareness grows, more consumers focus on their dietary habits and overall health status (Ghufran et al., 2022). Against this backdrop, the demand for healthy food continues to rise, leading to significant shifts in consumer purchasing behavior (Ding et al., 2022). However, numerous factors impact consumers' decisions regarding healthy food consumption, resulting in a substantial disparity between consumption intentions and actual decisions (Ljubičić et al., 2023; Xu et al., 2023). Household consumption behaviors have been shown to impact resource consumption, environmental quality, and climate change. Changes in consumption behavior and willingness to purchase healthy foods can significantly contribute to sustainable development (Shahbaz et al., 2022). According to the precautionary saving theory, uncertainty in income and expenditure will increase residents' precautionary savings and reduce residents' current consumption. Improving the social security system can alleviate the uncertainty of income and expenditure, reduce precautionary savings, and increase residents' consumption (Liu and Hu, 2022). Therefore, one of the solutions to the problem of stimulating healthy food consumption is reducing residents' income and expenditure uncertainty by improving the social security system. Whether the social security system addresses the gap between intention and decision-making and promotes healthy food consumption at home still requires in-depth discussion and evaluation. In summary, formulating and implementing a scientific and adequate social security system to promote citizens to narrow the gap between consumption intentions and actual decision-making is a challenge facing the Chinese government.

Healthy food consumption encompasses individuals' daily choices and purchases to provide nutrition, promote health, and prevent diseases. The primary objective of healthy food consumption is to fulfill the body's requirements for a range of nutrients through a well-balanced and diverse diet (Kennedy et al., 2023; Le et al., 2023). Emphasizing the intake of various nutrients, including carbohydrates, proteins, fats, vitamins, and minerals, healthy food consumption aims to ensure the body's normal functioning and overall wellbeing (Caso et al., 2022). It advocates the inclusion of a variety of foods such as fresh fruits, vegetables, whole grains, healthy protein sources (e.g., fish, chicken, beans), and moderate amounts of healthy fats (Sim and Cheon, 2019). Healthy food consumption also encourages the reduction of processed foods with excessive ingredients like high sugar, high salt, high fat, and artificial additives to mitigate the risks of obesity and other health issues associated with overconsumption (Werthmann et al., 2023).

Health is an essential factor affecting personal and family consumption. Developing the consumption habit of purchasing healthy food can improve the body's immunity and reduce unnecessary medical expenses. On the contrary, health risks may squeeze consumer demand and disincentive affect consumer behavior. Long-term care insurance (LTCI) is vital in resisting economic losses or care burdens caused by risks such as poor health and disability. As a result, LTCI has increasingly become a focal point in discussions on social security, health consumption, and medical care in recent years (Ameriks et al., 2020). This insurance system, already implemented in countries such as Japan, South Korea, and the United States, is designed to offer financial support and services to elderly and disabled individuals—those with long-term care needs (Liu et al., 2023). Implementing LTCI can potentially lead to heightened awareness of health status and long-term care requirements, influencing people's demand for and consumption of healthy food. In theory, LTCI has the potential to decrease unforeseen household expenditures, resulting in a reduction of precautionary savings in the current period and an increase in the net income and consumption level of elderly households (Imrohoroğlu and Zhao, 2018; Liu et al., 2023). Beyond its direct impact on household finances, implementing LTCI will likely have a discernible effect on consumer behavior (Kopecky and Koreshkova, 2014).

Consumers are more concerned about health and long-term care-related products and services, tend to choose insurance products with comprehensive coverage, increase the demand for healthy food and medical care equipment, and increase their purchasing power due to financial support (Bronchetti, 2012; Lachowska and Myck, 2018; Liu et al., 2023). The introduction of LTCI policies has led to a deeper understanding of the importance of elderly care and disease management (Ameriks et al., 2020). Consumers are more aware that they may need LTCI and, therefore, are more inclined to choose products and services related to health and long-term care in their purchasing decisions (Feng Z. et al., 2020). Implementing LTCI policies has made people pay more attention to health issues and realize the importance of diet to health (Kim and Mitra, 2022). Therefore, by participating in LTCI policies, consumers may be more inclined to choose healthy food consumption in their purchasing decision-making behavior to maintain good health and prevent diseases. Based on the above logic, we use the ten-issue panel data of the China Health and Nutrition Survey (CHNS) from 1989 to 2015 and adopt a difference-in-difference (DID) framework to conduct an empirical analysis on the impact of healthy food consumption on households participating in the LTCI pilot and analyze the heterogeneous impact of consumption behavior.

This study is one of the few endeavors employing representative microdata from China to scrutinize the effects of LTCI policies. More significantly, it bears substantial policy implications for fostering healthy dietary choices. Based on the study findings, policymakers can provide appropriate recommendations for transforming public demand for medical care and promoting daily healthy food consumption, thus effectively enhancing individuals' physical wellbeing. Balancing the promotion of a healthy diet with household consumption budget constraints is a universal challenge in health. As highlighted by Cutler (2010), scholars recognize the potential avoidance of malnutrition and unhealthy diet-related issues. However, consensus on effective avoidance strategies remains elusive. Our findings underscore that the nascent LTCI policy in China is an effective catalyst for reshaping consumer behavior, steering it toward healthier food consumption. This finding aligns with the current trajectory of China's medical service delivery system reform, emphasizing resident health over mere service provision. Consequently, this study provides a valuable reference for ongoing policy formulation to enhance the dietary quality of families in China.

2 Literature review

2.1 Research on consumer behavior and healthy food consumption

Consumption behavior is the main driving force for consumption decisions, and consumers' preferences for goods will affect actual consumption (Lee and Yun, 2015; Wang and Li, 2023). As people's awareness of health increases, more and more consumers begin to pay attention to their eating habits and health status (Luo et al., 2021). Against this background, the demand for healthy food continues growing, and consumer purchasing behavior has undergone significant changes (Ding et al., 2022). Healthy food consumption has become an important trend in today's society, representing people's pursuit of health and longevity (Eyinade et al., 2021). Most studies show that consumers are increasingly inclined to choose healthy foods because they realize the importance of diet for good health (Eyinade et al., 2021; Ding et al., 2022; Ghufran et al., 2022). Consumers pay more attention to nutritional value and are more willing to pay more time and money for high—quality, healthy food (Ljubičić et al., 2023). Consumer purchasing behavior is often affected by many factors. First, personal health awareness and health knowledge play a crucial role in consumer purchasing behavior (Parashar et al., 2023). During the COVID-19 pandemic outbreak, people suffered economic turbulence, social instability, and food insecurity (Shahzad et al., 2021). A few studies have discussed the relationship and impact of COVID-19 on food insecurity, food purchasing costs, and online food purchase behavior. Adverse income shocks and unemployment have affected the cost of food purchases and made it difficult for people to afford healthy food, further causing malnutrition and personal health (Shahzad et al., 2023). With the hardship behind us, the emphasis on health and the demand for healthy food has increased. In addition, the quarantine of the epidemic drove online consumption, and consumers' purchasing behavior shifted from offline to online. Shahzad et al. (2022) found that consumers purchasing healthy online food increased dramatically. The research of Yang et al. (2023) pointed out that consumers' understanding of healthy foods has gradually increased with the popularization of health education and the dissemination of information. They pay more attention to the nutritional content and choose healthy foods that meet their needs through comparison and evaluation (Xu et al., 2023).

Secondly, advertising and publicity also influence consumer purchasing behavior (Boyland et al., 2016). Food manufacturers and sellers convey information about healthy food to consumers through various channels and methods. Advertisements emphasize products' healthy ingredients, functions, and effects, establishing consumers' health-related perceptions and expectations (Royo-Bordonada et al., 2016). These advertisements often influence consumers and regard them as essential references for purchasing decisions. In addition, the rise of social media has also had a massive impact on consumer purchasing behavior (Singh and Glińska-Neweś, 2022). People share their dietary preferences, healthy eating experiences, and purchasing experiences on social media, which provides opportunities for other consumers to refer to and learn from (Xu et al., 2023). Consumers can learn about other people's reviews and recommendations of healthy foods through social media, influencing their purchasing decisions.

Finally, price and convenience are also important factors consumers consider when purchasing healthy foods (Bai et al., 2021). Although the development of the health food market has made such products more popular and diversified, their prices are often relatively high (Dominguez-Viera et al., 2022). Consumers need to make a trade-off between health and the economy and choose healthy foods that suit them. In addition, the convenience of purchasing healthy food is also an important factor for consumers to consider. In modern life with busy work, consumers are more inclined to choose healthy, convenient, and accessible foods (Goossensen et al., 2023).

2.2 Research on LTCI policy, consumer behavior and healthy food consumption

The above analysis shows that factors such as consumers' health awareness, health knowledge, advertising, social media, price, and convenience jointly affect consumers' decision-making on healthy food consumption. The emergence of the LTCI policy provides families with financial support and services (Imrohoroğlu and Zhao, 2018; Liu et al., 2023). Existing research focuses on the following aspects. First, LTCI policies can increase people's attention and awareness of health. Liu et al. (2023) believe that since long-term care insurance targets groups prone to disease, such as the elderly, these groups pay more attention to their health conditions and long-term care needs. They are usually more inclined to choose healthy foods to maintain good health and reduce disease risk. Secondly, the LTCI policy has spawned a huge long-term care service market, including health food and related industries (Fu et al., 2017). As the need for LTCI, so does the demand for care services and products (Lei et al., 2022). This provides enormous business opportunities for healthy food production and sales companies. Third, LTCI policy emphasizes prevention and health management (Feng J. et al., 2020). The policy encourages people to adopt a healthy lifestyle, including a reasonable diet and balanced nutrition. Under the guidance of policies, people have paid more attention to dietary health and begun to pay more attention to food selection and consumption (Zhu and Österle, 2017). They are more inclined to buy healthy foods, such as organic foods, natural foods, low salt and low sugar foods, etc., to maintain good health and reduce disease risk. Finally, the LTCI policy promotes increased healthy food consumption through economic support (Liu et al., 2023). LTCI provides financial subsidies and services to eligible beneficiaries, allowing them to pay for long-term care-related expenses better (Kim and Mitra, 2022), which also means they have more financial ability to purchase healthy foods and improve their diet.

3 Background

3.1 LTCI policy background

LTCI usually refers to a social insurance system that raises funds through social mutual aid to provide funds or service guarantees for the primary life care of middle-aged and elderly disabled people and medical care closely related to bear life (Liu et al., 2023). Many countries, including Germany, Japan, and the Netherlands, have established different long-term care insurance systems internationally. Qingdao, China, learned from other countries' LTCI implementation experience and issued the "Opinions on Establishing a Long-term Medical Care Insurance System (Trial)" in 2012, leading in implementing the LTCI system in cities and towns. In 2015, this system was expanded to rural areas, becoming the first region in the country to achieve full coverage of LTCI. In 2016, China issued the "Guiding Opinions on Carrying out the Pilot Program of Long-term Care Insurance System," and 15 cities began to pilot the LTCI system. In September 2020, the National Medical Security Administration issued the "Guiding Opinions on Expanding the Pilot Program of the Long-term Care Insurance System", adding 14 pilot cities. In 2022, the State Council of China issued the "14th Five-Year Plan for National Aging Development and Elderly Care Service System", proposing to steadily establish the LTCI system and improve the LTCI handling service system. In 2022, the China Banking and Insurance Regulatory Commission issued the "Notice on Carrying out the Pilot Program of Liability Conversion Business between Life Insurance and Long-term Care Insurance" to guide life insurance companies to carry out the pilot program of liability conversion business between life insurance and LTCI and increase the supply path of commercial LTCI. Twelve years have passed since the first batch of pilot policies were introduced, and China's LTCI protection results are beginning to show. According to data from the "2021 National Aging Development Bulletin", as of the end of 2021, a total of 144.607 million people in China have participated in LTCI, enjoying The number of people receiving benefits was 1.087 million, the fund income for the year was 26.06 billion yuan, and the fund expenditure was 16.84 billion yuan.

Currently, China's LTCI has the following characteristics: First, the funding source of LTCI in various pilot areas is mainly from the medical insurance coordination fund, supplemented by unit supplementary medical insurance, individual new contributions, and financial subsidies. Fund disbursements are closely tied to disability assessments and payment criteria (Luo et al., 2024). Second, the scope and degree of protection continue to deepen (Lei et al., 2022). The scope of protection in pilot cities such as Guangzhou and Shangrao has been expanded from those insured by the basic medical insurance for urban employees to those insured by the basic medical insurance for urban and rural residents. Based on protecting the severely disabled groups, pilot cities such as Chengdu and Qingdao have gradually included groups with moderate to mild disabilities and dementia. Third, the security model mainly includes institutional care and home care. Some pilot cities are further refined. For example, Jingmen in Hubei is divided into four categories: home-based part-time, home-based full-time, elderly care institutions, and medical institutions, and Beijing Shijingshan is divided into three categories: home-based self-care, home-based care, and institutional care.

3.2 Other existing food consumption policies

Since 2001, the Chinese government has promulgated the "Regulations on the Safety Management of Genetically Modified Organisms", the "Measures for the Safety Management of Agricultural Genetically Modified Organisms," the "Measures for the Safety Management of the Import of Agricultural Genetically Modified Organisms," and the "Measures for the Management of the Labeling of Agricultural Genetically Modified Organisms." The above regulations and "Measures" implement different management methods for importing, exporting, and transiting genetically modified agricultural products. Among them, the focus of control is importing genetically modified agricultural products. The control measures are implementing a safety-graded management evaluation system and a mandatory labeling system for imported products (Sun et al., 2021). On the one hand, the supply of raw materials in the feed industry and soybean crushing industry continues to increase, which promotes the rapid development of domestic livestock, livestock, and poultry breeding industries and ensures sufficient domestic supply of meat, eggs, oils, and milk. On the other hand, the large-scale import of genetically modified products has lowered the price of genetically modified products and reduced the input costs of domestic livestock, animal husbandry, and poultry breeding industries. Due to the stickiness of food prices in the short term, competitors will produce more related products, decreasing related food prices and reducing the marginal budget share of related food for urban residents. Implementing the mandatory labeling system for genetically modified foods has both a positive promoting effect and a negative inhibiting effect on the marginal budget share of urban residents' relevant food.

In terms of green food consumption, China has successively promulgated several green food policies in recent years, such as the "2021 Action Plan for Standardizing the Use of Green Food Labels" and the "Outline of the 14th Five-Year Plan Development Plan for the Green Food Industry". These policies are mainly supply-side policies that use market supervision to affect producer investment, production costs, and access conditions, and demand-side policies such as publicity and promoting consumer consumption tendencies and behaviors. They are binding policies that set standards and regulate certification (Zhu et al., 2013). These policies focus on food safety and quality, vigorously promote the development of the green food market, effectively improve consumers' environmental awareness and information acquisition capabilities, and improve the current situation where consumers do not understand and do not trust green food.

4 Methodology

4.1 Data source

This study used panel data from the ten issues of the China Health and Nutrition Survey (CHNS) from 1989 to 2015. CHNS is a long-term, national-level population health survey project commissioned by the University of North Carolina in the United States and the Ministry of Health of China. The project began in 1989 to understand the Chinese population's nutritional status, health status, and lifestyle and the impact of these factors on chronic diseases. The project has spanned over 30 years and has become one of the world's most influential population health survey projects. CHNS uses a multi-stage sampling method to select representative samples from various cities and villages in China and collects data on individuals, families, and communities through face-to-face questionnaires and biometric measurements. The survey contains basic personal information, such as diet, nutrition, lifestyle, health status, medical care, and other aspects. CHNS adopts the principle of multi-stage sampling method. In terms of cities, provincial capital cities were selected, and one medium-sized city with poor economic development was randomly selected. In rural areas, counties in the province are divided into three categories: high, medium, and low levels of economic development. One county is selected from each high-level and low-level category, and two counties are selected from the medium-level categories. Four survey points were determined in each city or county based on a random multi-stage cluster sampling. The city selected two urban neighborhood committees and two suburban villages, and the county selected one neighborhood committee and three villages where the county government is located. The survey is divided into three scales: community, household, and individual. CHNS considers macro factors such as China's geographical environment, economic development level, population distribution characteristics, and urban and rural structure differences, covering China's eastern, central, western, and northeastern regions. This data highly represents China's overall situation and is highly authoritative and reliable (Chen et al., 2023). The content of CHNS involves nine major parts, including nutritional diet, health care and medical insurance, daily activities, and physical condition. The data in this article mainly applies to the nutritional dietary structure survey part of CHNS. The nutritional dietary structure survey uses a continuous 3-day, 24-h recall method to collect food intake information of family members aged two and above in all surveyed households. The main survey indicators include household food consumption in 3 days, statistics per person per day, name of daily meals, preparation method, preparation place, eating time, etc. This data can be used to measure the consumption of healthy food among urban and rural residents in China. Therefore, the CHNS database is a good fit for the topic of this study.

Moreover, the LTCI policy in this study was piloted in 2012, and the time node of the CHNS data meets the research requirements, providing a double difference setting for this article. The reason is that the CHNS data's time node is consistent with this policy's implementation time. This temporal coincidence provides us with a setting for DID analysis. DID can evaluate the impact of the LTCI policy on research subjects by comparing the differences before and after the implementation of the policy and between the treatment group and the control group affected by the policy. Therefore, the consistency of the time nodes of the CHNS data with the pilot time of the LTCI policy can provide an effective research design, allowing us to use the DID method to evaluate the impact of the policy on the research objects. We eliminated data with missing values in household identification codes, food intake, preparation methods, and eating time, eliminated outlier samples with higher calorie intake than five standard deviations, and obtained 41,878 samples.

4.2 Identification strategy

The LTCI policy lasted for ten years in China, and there were significant regional differences. It was a standard quasi-natural experiment. The reasons why LTCI policy can be regarded as a quasi-natural experiment are: First, LTCI policy pilots are usually implemented by the government in specific regions or groups, and this selection is often based on specific standards or needs rather than random selection. Therefore, implementing this policy has a certain "naturalness" and is not entirely controlled by researchers (Lei et al., 2022). Second, when the LTCI policy is implemented on a pilot basis, there are usually other regions or groups where the policy has not been implemented, and these regions or groups can serve as control groups. Researchers can compare the differences between pilot areas and control groups before and after policy implementation to evaluate the effectiveness of the policy. Third, implementing LTCI policy pilots allows researchers to compare changes before and after implementation in the same region or population. Such time series comparisons help identify the impact of policies. Finally, because LTCI policy pilots are conducted under real-world conditions, the results tend to have high external validity, that is, the research findings can be better generalized to other similar situations. The above four characteristics of LTCI policy are consistent with the definition of the quasi-natural experiment.

This study divided the sample into households affected by LTCI policy (experimental group) and households unaffected by

LTCI policy (control group). The DID method was used to identify whether implementing LTCI affected household healthy food consumption. DID is an econometric method used to evaluate the effectiveness of policies or interventions. This method estimates the causal effect of a policy by comparing changes before and after the policy is implemented (differences in time) and changes between a group that implements the policy and a control group that does not implement the policy (differences between groups) (Bertrand et al., 2004; Ma et al., 2023b). The principle of DID is to calculate the changes in the experimental group before and after the policy is implemented (the first difference), then calculate the changes in the control group during the same period (the second difference), and finally calculate the difference between the two differences (i.e., the experimental group's change minus the change in the control group). This result represents the net effect of policy implementation, that is, the effect after removing the effects of time trends and other non-policy factors. DID is suitable for this study because LTCI policy pilots are often conducted in specific regions, which provides conditions for selecting experimental and control groups, making DID a suitable tool for evaluating policy effects. We refer to the method of Liu et al. (2023) and set the baseline regression as follow Equation (1):

$$Y_{it} = a_0 + \beta LTCI_i \times Post_t + \gamma X_{it} + \eta_i + \omega_t + \varepsilon_{it} \quad (1)$$

where, Y_{it} represents healthy meal preparation methods, whether the meals are processed foods, daily meal quantity, and the number of healthy preparation methods in the daily meal quantity. These indicators indicate household consumption of healthy foods. $LTCI_i \times Post_t$ is the interaction term of the dummy variable before and after the treatment group implements the LTCI policy. The interaction term coefficient β is this study's core coefficient of concern, representing the difference in outcome variables between households and other regions caused by participation in the LTCI policy. Based on this, we examine the policy effect of LTCI, that is, whether LTCI affects household consumption behavior and healthy food consumption. X_{it} is a set of control variables at the family level, including gender, place of birth, marital and ethnicity, family income and work intensity, self-rated health, disease history, tobacco and alcohol history, household cleaning water, and household hygiene. By controlling the above variables, this study can more accurately estimate the impact of implementing LTCI on household consumption behavior and healthy food consumption while reducing the bias caused by these unobserved confounding variables (Chen et al., 2023). In this way, the findings are more likely to reflect the effects of long-term care insurance policies themselves rather than the effects of other related factors. The specific reasons and measurement methods for selecting these variables are detailed below. η_i is the individual fixed effect. ω_t is the year-fixed effect. ε_{it} represents the disturbance term and uses robust standard errors clustered on the household dimension to alleviate the impact of individual-level related factors on the estimation results.

4.3 Variable selection and processing

4.3.1 Dependent variable (Y_{it})

This study refers to the research ideas of previous literature (Feng J. et al., 2020; Dominguez-Viera et al., 2022; Le et al., 2023; Werthmann et al., 2023). Meal preparation methods (HMPM) are dummy variables indicating that households used healthy cooking methods to prepare their daily meals in the year of the survey. CHNS data includes cooking methods such as boiling, stir-frying, frying, steaming, drying, cooked food, baking, and raw eating. Healthy food preparation methods include boiling, steaming, and raw eating. This study states that when family meals are prepared using these three methods, the value of Healthy meal preparation methods is 1; otherwise, it is 0. Whether the meal is processed food (NPF) is a dummy variable indicating whether the family often consumes processed food in their daily meals in the year of the survey. This study sets the value of Non-processed food as 1 when the family diet does not include processed food; otherwise, it is 0. Daily meal quantity (DMQ) is a household's total daily meal intake in the year of the survey. CHNS data reports households' total daily food consumption in grams. This study uses the natural logarithm to measure daily meal quantities. The reasons for using natural logarithm to measure are: First, this method can reduce the impact of large differences in actual values in CHNS data on regression, making the data distribution closer to a normal distribution. Second, after log transformation, the coefficients of the model estimates can be interpreted as percentage changes, which is a common way of interpretation in economics. Third, logarithmic transformation can linearize nonlinear relationships, allowing linear models to fit the data better. In economic and social science research, many relationships between variables may be nonlinear on the original scale, and log-transformed linear relationships are more accessible to interpret and model. The number of healthy food preparation methods in the number of daily meals (HFC) is the interaction term between the number of meals a household consumes daily in the year of the survey and whether it is processed food. It is used to reflect the structure of healthy food consumption. The reasons for using interaction terms to measure are: first, healthy food consumption depends not only on the quantity of food but also on the quality of the food. Processed foods are often considered less healthy than fresh foods. For example, when the number of meals per day increases and the number of processed foods decreases, the interaction term between them reflects a healthier food consumption structure in the household. Therefore, the interaction term can help us accurately measure households' healthy food consumption structure. Second, interaction terms can reveal household behavioral patterns when consuming different types of food. For example, households may have different consumption tendencies when consuming processed and non-processed foods, and this difference can be captured through interaction terms. Third, if implementing LTCI causes households to be more inclined to consume healthy foods, this change may manifest in households reducing their consumption of processed foods while increasing their consumption of non-processed foods. The interaction term can serve as an indicator of this behavioral change. Fourth, without interaction terms, meal size or processed food variables alone may not adequately control other factors influencing healthy food consumption. Interaction terms can control these potential confounders and provide more accurate estimates.

4.3.2 Independent variable ($LTCI_i$ × $Post_t$)

$LTCI_i$ is a dummy variable indicating whether the household belongs to the four provinces and cities of Beijing, Jiangsu, Shandong, Shanghai, and Chongqing. $Post_t$ is a dummy variable for policy implementation. Since there are differences in policy implementation time among provinces and cities, this study assigns values based on the actual implementation time. Specifically, when $t \geq 2012$, the $Post_t$ value corresponding to Beijing is 1; when $t \geq 2013$, the $Post_t$ value corresponding to Jiangsu and Shandong is 1; when $t \geq 2014$, the $Post_t$ value corresponding to Jiangsu and Shandong is 1; when $t = 2015$, the $Post_t$ value corresponding to Chongqing is 1; otherwise, the value of postt is 0.

4.3.3 Control variables

We drew on relevant studies (Zhu and Österle, 2017; Min et al., 2021; Chen et al., 2023; Fang et al., 2023) and selected the following control variables at the household level. There may be differences in the consumer behavior of men and women, including preferences for healthy foods and purchasing decisions. Therefore, the gender of the household head (Gender) is measured according to the CHNS statistical indicators: male is 1 and female is 2. Different regions may have different eating habits and types of food available, which may affect household food consumption. Therefore, the birthplace (Birthplace) of the household head is measured according to the CHNS statistical indicators, that is, if he was born in a town, it is 1, otherwise it is 0. Married or partnered individuals may have different consumption patterns, particularly food purchases and household expenditures. Therefore, the household head's marital status (Marry) is measured as 1 according to the married value set in CHNS and 0 otherwise. Families of different ethnic backgrounds may have different eating habits and cultural preferences, affecting their food choices. Therefore, the ethnic group (Ethnic) of the household head is measured as 1 according to the ethnic minority set in CHNS and 0 otherwise. Income level is an essential factor affecting spending power and consumption choices, and high-income families may be more inclined to purchase healthy foods. Therefore, the family's annual income (Income) is measured by summing up the various household income statistics from CHNS and taking the natural logarithm. Individuals with high work intensity may have less time to prepare healthy foods, affecting healthy food consumption at home. Therefore, the family work intensity (Activity Level) is measured according to the CHNS statistical indicators, that is, the value of moderate physical activity and below and the inability to work is 1; otherwise, it is 0. Individuals' health evaluations may influence their lifestyle and food consumption choices. Therefore, the self-evaluation of family health (Self-health evaluation) is based on the indicators of CHNS statistics (compared with other people of the same age, how do you think your current health status is?) and the choice of "very good" and "good" is 1, otherwise 0. Family members with a history of illness may require special diets, which can affect the family's food consumption patterns. Therefore, the family's medical history is measured according to the CHNS statistical indicators, that is, the value of family members suffering from chronic diseases, hypertension, diabetes, myocardial infarction, stroke, tumors and other diseases is 1, otherwise it is 0. Smoking and drinking habits may be associated with unhealthy lifestyles, which may affect household demand for healthy foods. Therefore, the family's tobacco and alcohol history (Tobacco and alcohol) is measured according to the CHNS statistical indicators, that is, the value of a family member who smokes and drinks more than 2 times a month is 1, otherwise it is 0. Household cleaning water and sanitation conditions may affect family members' health status and demand for healthy foods. Therefore, whether a household uses clean water (Cleaning water) is measured according to the CHNS statistical indicators (the value of using clean tap water is 1. Otherwise, it is 0). Home hygiene is measured according to the CHNS statistical indicators, that is, if there is little or no feces around the room, the value is 1, otherwise it is 0. Descriptive statistics of the above variables are shown in Table 1.

TABLE 1 Descriptive statistics.

Variables	Obs	Mean	Std. dev.	Min	Max
HMPM	41878	0.521	0.500	0	1
NPF	41878	0.071	0.257	0	1
DMQ	41878	1.885	2.041	-4.605	7.856
HFC	41878	0.321	1.181	0	7.320
$LTCI_i \times Post_t$	41,878	0.020	0.141	0	1
Gender	41,374	1.445	0.497	1	2
Birthplace	41,878	0.001	0.037	0	1
Marry	41,878	0.478	0.500	0	1
Ethnic	41,878	0.007	0.085	0	1
Income	41,878	2.439	3.337	0	13.71
Activity level	41,878	0.944	0.231	0	1
Self-health evaluation	41,878	0.245	0.430	0	1
Medical history	41,878	0.123	0.328	0	1
Tobacco and alcohol	41,878	0.292	0.455	0	1
Cleaning water	41,878	0.007	0.084	0	1
Home hygiene	41,878	0.684	0.465	0	1

4.4 Variable mean test

This study uses the mean test to determine whether there is a significant difference in the overall means represented by the experimental and control groups. Table 2 reports the statistical characteristics of the differences between the control and experimental groups. Among them, the healthy food consumption of households participating in the LTCI policy is greater than that of non-participating households. This result shows the difference in changes in healthy food consumption between Chinese households before and after receiving treatment and households that did not

TABLE 2 Variable group mean test.

	Before policy	After policy	Unconditional difference
HMPM	0.532	0.758	−0.226***
NPF	0.073	0.335	−0.262***
DMQ	1.924	3.451	−1.527***
HFC	0.328	0.469	−0.141***
Gender	1.446	1.435	0.010
Birthplace	0.001	0.018	−0.017***
Marry	0.475	0.635	−0.160***
Ethnic	0.007	0	0.007**
Income	2.457	1.578	0.879***
Activity level	0.942	1	−0.058***
Self-health evaluation	0.241	0.449	−0.208***
Medical history	0.120	0.282	−0.162***
Tobacco and alcohol	0.292	0.297	−0.005
Cleaning water	0.005	0.096	−0.091***
Home hygiene	0.681	0.807	−0.126***

***p < 0.01, **p < 0.05

TABLE 3 Difference-in-differences regression results.

	HMPM	NPF	DMQ	HFC
	(1)	(2)	(3)	(4)
$LTCI_i \times Post_t$	0.045***	0.033***	0.198***	0.194***
	(0.013)	(0.010)	(0.042)	(0.047)
Gender	0.004	0.004**	−0.037	0.019*
	(0.014)	(0.002)	(0.038)	(0.010)
Birthplace	0.107**	0.033***	−0.088***	0.094***
	(0.047)	(0.006)	(0.012)	(0.023)
Marry	0.007	0.000	0.036***	0.005
	(0.005)	(0.001)	(0.011)	(0.007)
Ethnic	0.038	−0.003	−0.047	0.006
	(0.030)	(0.005)	(0.086)	(0.024)
Income	−0.000	−0.000	0.002	−0.000
	(0.001)	(0.000)	(0.002)	(0.001)
Activity level	−0.008	0.001	0.138***	0.018***
	(0.012)	(0.002)	(0.025)	(0.002)
Self-health evaluation	0.006	0.003***	0.085***	0.014**
	(0.008)	(0.001)	(0.017)	(0.006)
Medical history	0.017**	−0.001	0.018***	0.003
	(0.008)	(0.003)	(0.007)	(0.013)
Tobacco and alcohol	0.008	−0.001	0.044***	−0.003
	(0.006)	(0.002)	(0.013)	(0.008)
Cleaning water	−0.001	0.029**	0.002	0.149**
	(0.017)	(0.013)	(0.042)	(0.061)
Home hygiene	0.004	0.001	0.038***	0.003
	(0.006)	(0.001)	(0.015)	(0.007)
Constant	0.516***	0.061***	1.732***	0.254***
	(0.024)	(0.004)	(0.061)	(0.020)
Year FE	Control	Control	Control	Control
Household FE	Control	Control	Control	Control
R^2	0.234	0.891	0.877	0.870
Obs	40,397	36,909	36,909	36,909

***p < 0.01, **p < 0.05, *p < 0.1. Clustered robust standard errors at the household level are in parentheses.

participate in other cities. However, the impact LTCI has had remains to be seen. Further empirical analysis is needed later. There are no significant differences in gender and tobacco and alcohol history of household heads participating in the LTCI policy, indicating that these two characteristics will not change due to policy implementation. Most variables have increased significantly compared with before participating in the LTCI policy. Therefore, the control variables selected in this study can effectively control the inherent differences between the control and experimental groups, thereby obtaining more reliable policy effect evaluation results.

5 Results

5.1 The impact of LTCI policy on healthy food consumption among Chinese households

According to the empirical method introduced above, this article uses Stata17 software to comprehensively identify whether implementing the LTCI policy affects household healthy food consumption. The empirical results are shown in Table 3.

It can be found from column (1) of Table 3 that the estimated coefficient of $LTCI_i \times Post_t$ is significant at 0.045 at the 1% significance level. This result shows that implementing LTCI can increase the frequency of adopting healthy diet preparation methods by 0.045 times for families participating in the policy compared with families not participating. This result means that implementing LTCI policies may prompt families to adopt healthier diet preparation methods, thus positively impacting families' eating habits and health. Column (2) shows that the estimated coefficient of $LTCI_i \times Post_t$ is significant at 0.033 at the 1% significance level. This result shows that implementing LTCI can increase the frequency of diets that do not include processed foods for households participating in the policy by 0.033 units compared with households not participating. Considering that processed foods often contain more additives and high-calorie ingredients, this change may help families eat healthier and reduce the negative health effects of processed foods. Column (3) shows that the estimated coefficient of LTCI is significant at 0.198 at the 1% significance level, indicating that implementing LTCI can increase the daily meal consumption of households participating in the policy by 0.198% compared with households not participating in the policy. After conversion into actual dietary consumption, households participating in the policy increased their daily dietary consumption by an average of 1.219 grams compared with households not participating in LTCI. This result means that LTCI policies may prompt households to increase their food consumption by a certain amount in their daily meals. In a practical sense, this may mean that households purchase more fresh ingredients or higher-quality food when financial conditions allow, thereby improving their diet and nutritional intake. Column (4) still shows that the estimated coefficient of $LTCI_i \times Post_t$ is significant at 0.194 at the 1% significance level. This result shows that overall, implementing LTCI can increase the healthy food consumption structure of households participating in the policy by 0.194 units compared with households not participating. The practical implication of this result is that LTCI policies may impact households' dietary patterns, especially regarding processed foods. Households participating in the policy are more likely to consume less processed food or to pay more attention to quantity and quality when consuming processed food. Considering the potential health effects of processed foods, this change may help families improve their diets, reduce the adverse health effects of processed foods, and improve overall nutritional status. The regression results show that participating in LTCI policies can effectively increase Chinese families' healthy food consumption. Next, we analyze how LTCI participation may influence healthy food consumption behavior.

5.2 Mechanism test

The above simple analysis shows that risk prevention is the primary purpose of LTCI, and implementing LTCI can increase the consumption of healthy food related to future disability risk. In order to verify this mechanism, this paper conducts regression using self-rated health as the mediating variable. The mediating effect model is usually used to study how one variable affects another mediating variable, thereby affecting the outcome variable (Yang and Ma, 2023). We construct the following mediating effect model [Equation (2) and Equation (3)]:

$$M_{it} = a_1 + \phi_1 LTCI_i \times Post_t + \gamma X_{it} + \eta_i + \omega_t + \varepsilon_{it} \quad (2)$$

$$Y_{it} = a_2 + \phi_2 LTCI_i \times Post_t + \delta M_{it} + \gamma X_{it} + \eta_i + \omega_t + \varepsilon_{it} \quad (3)$$

where, M_{it} is the mediating variable, that is, the family's self-evaluation of health (Self-health evaluation). Suppose ϕ_1 passes the significance test. In that case, a relationship exists between implementing LTCI and the family's self-rated health, and the mediation effect is initially established. Then, if ϕ_2 and δ both pass the significance test, the mediation effect mechanism is established. LTCI affects the family's healthy food consumption by affecting the family's self-evaluated health. The regression results are shown in Table 4.

Column (1) shows that the estimated coefficient of LTCI is significantly 0.012 at the 1% significance level, indicating that LTCI effectively improves the self-rated health of families, consistent with existing research findings (Imrohoroğlu and Zhao, 2018). Except for column (2), which does not pass the mediating effect test, the others all pass the mediating effect test. It is verified that LTCI increases families' healthy diet preparation methods, daily meal consumption, and healthy food consumption structure through risk prevention mechanisms. Families often purchase LTCI to deal with underlying health problems and long-term care needs. Such insurance policies may remind families to pay more attention to health issues and enhance their health awareness, affecting household consumer behavior (Imrohoroğlu and Zhao, 2018; Ariaans et al., 2021). Family members may be more inclined to choose healthy foods to maintain good health. In addition, by participating in LTCI, families may pay more attention to the importance of disease prevention and form healthy consumption behaviors (Liu et al., 2023). Healthy foods are often packed with nutrients that help boost immunity and reduce disease risk. As a result, households may increase their consumption of healthy foods to prevent potential health problems. Most importantly, participating in LTCI may require certain financial investments (Dominguez-Viera et al., 2022). In order to cope with potential medical and long-term care costs, households may re-evaluate their budgets, adjust consumption preferences and behaviors (Eyinade et al., 2021), and regard healthy food consumption as an essential expenditure item, resulting in households increasing their consumption of healthy foods. These results verify and supplement the existing literature on the effects of social insurance consumption channels.

5.3 Robustness tests

5.3.1 Parallel trend test

Parallel trend testing is an essential prerequisite for using the DID model. The primary purpose is to evaluate whether the impact of a particular policy, intervention, or event on a specific outcome variable is statistically significant (Ma et al., 2023b). In a parallel trend test, a control group and an experimental group are usually selected, and the trend of a certain outcome variable is used as the evaluation index. By comparing whether the trends of the treated group and the untreated group before a certain time point are parallel and whether the trend after that time point is significantly different, the size and statistical significance of the causal effect between the treatment group and the non-treatment group can be assessed. Parallel trend testing aims to reduce the confounding effects caused by other potential influencing factors to more accurately assess the impact of policies, interventions, or events on a specific outcome variable. This study conducted a parallel trend test by setting the base period to the year before LTCI was implemented.

Figure 1 reports the results of the parallel trend test. The changing trend of the estimated coefficients of LTCI on the four dependent variables in the three periods before the policy was implemented was relatively flat. It did not pass the significance test at the 1% level, indicating that before implementing the LTCI policy, the healthy food consumption of households in the control and experimental groups was not the same. There is no noticeable difference, satisfying the parallel trend assumption. In the year of LTCI implementation and subsequent years, household healthy food consumption in the experimental group increased significantly.

TABLE 4 Mechanism test.

	Self-health evaluation	HMPM	NPF	DMQ	HFC
	(1)	(2)	(3)	(4)	(5)
$LTCI_i \times Post_t$	0.012***	0.034**	0.069***	0.189***	0.395***
	(0.004)	(0.011)	(0.015)	(0.052)	(0.070)
Self-health evaluation		0.221*	0.138	0.073***	0.507**
		(0.131)	(0.106)	(0.008)	(0.199)
Gender	−0.006	0.223**	0.015	0.540*	0.305
	(0.009)	(0.093)	(0.090)	(0.197)	(0.435)
Birthplace	0.017	0.071	0.055	−0.040	0.201
	(0.014)	(0.062)	(0.045)	(0.060)	(0.232)
Marry	−0.001	−0.014	−0.003	0.034**	0.006
	(0.001)	(0.011)	(0.005)	(0.018)	(0.025)
Ethnic	0.002*	0.171	0.001	−0.214	0.254
	(0.001)	(0.137)	(0.045)	(0.228)	(0.215)
Income	0.024	−0.001	−0.000	−0.001	0.002
	(0.143)	(0.002)	(0.001)	(0.004)	(0.005)
Activity level	0.005	−0.004	0.019	0.103*	0.143*
	(0.012)	(0.038)	(0.023)	(0.068)	(0.080)
Medical history	−0.001	−0.017	−0.004	0.017	−0.005
	(0.001)	(0.015)	(0.008)	(0.025)	(0.038)
Tobacco and alcohol	−0.023	0.002	0.001	0.009	−0.006
	(0.041)	(0.013)	(0.006)	(0.023)	(0.032)
Cleaning water	−0.003	−0.037	0.031*	−0.016	0.131*
	(0.003)	(0.029)	(0.018)	(0.055)	(0.089)
Home hygiene	0.001	−0.027*	−0.000	0.023	−0.007
	(0.001)	(0.015)	(0.008)	(0.029)	(0.040)
Constant	0.006	0.118	0.272**	2.306***	0.821
	(0.013)	(0.137)	(0.132)	(0.573)	(0.634)
Year FE	Control	Control	Control	Control	Control
Household FE	Control	Control	Control	Control	Control
R^2	0.508	0.484	0.871	0.926	0.848
Obs	41,878	40,397	36,909	36,909	36,909

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Clustered robust standard errors at the household level are in parentheses.

5.3.2 Placebo test

Although this study has controlled a large number of household characteristic variables in a quasi-natural experiment, there may still be some non-observed household characteristic factors that affect the evaluation results of the LTCI pilot policy. A potential threat is that central and local governments may have selected pilot cities based on predetermined city-level characteristics and been assigned non-randomly. We address this issue with a placebo test. If the model is a simultaneous point DID, refer to Liu and Lu (2015) and randomly select provinces and cities equal to the number of real pilots from all samples as the experimental group. However, due to the differences in pilot policy impact time in multi-time point DID, it is necessary to randomly generate the pseudo experimental group dummy variable $LTCI^{false}$ and the pseudo policy impact dummy variable $Post^{false}$ at the same time, that is, randomly select a sample period for each sample object as its policy time. Based on this, we use the following placebo test method to further ensure the estimation results' robustness. First, Stata software is used to construct 500 random shocks of the pseudo-LTCI pilot policy. Secondly, 1,700 households are randomly selected as the experimental group each time, and the policy time is randomly given, resulting in 500 groups of dummy variables $LTCI^{false} \times Post^{false}$. Third, the kernel density of 500 $LTCI^{false} \times Post^{false}$ and its P-Value distribution are presented in the figure. The results are

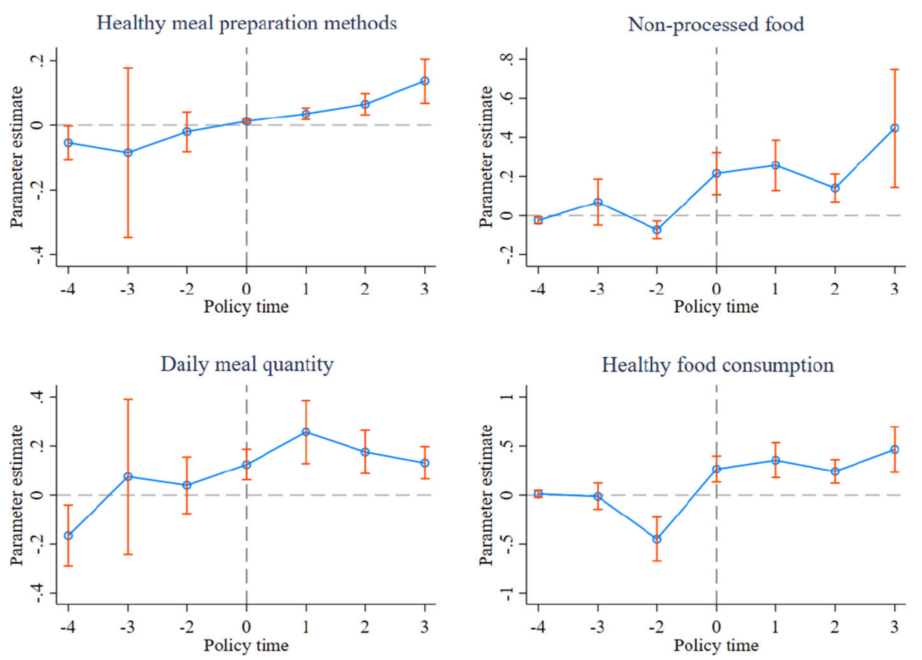

FIGURE 1
Parallel trend test.

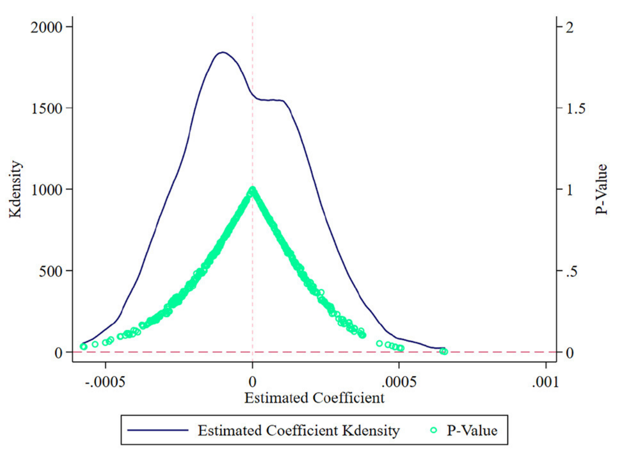

FIGURE 2
Placebo test.

shown in Figure 2. The false estimated coefficients generated during random processing are concentrated near 0, and the *P*-value are mostly higher than 0. The estimated coefficient of the actual policy is significantly different from the placebo test results. This result also shows, to a certain extent, that the quantitative evaluation results of this article are not significantly affected by this potential factor. The results are robust.

5.3.3 Semiparametric DID method

Similarly, this paper also conducts robustness testing through the semiparametric DID method (SDID) proposed by Abadie (2005). In the case of two periods of balanced panel data, this method uses weighting to balance the characteristics of the experimental and control group samples. It can be concluded that this method has a certain credibility even when the common trend is not completely satisfied. SDID is as follow Equation (4):

$$E\left[\frac{\Delta Y_t}{P\left(d_t=1\right)}\times\frac{d_t-\psi\left(X_b\right)}{1-\psi\left(X_b\right)}\right] \quad (4)$$

where, d_t represents whether it is the experimental group in period t, $P\left(d_t=1\right)$ represents the probability of the experimental group, $\psi\left(X_b\right)$ is the Abadie weight, which can be calculated through the linear probability model $\psi\left(X_b\right) = P\left(d_t=1|X_b\right)$. Houngbedji (2016) believes that SDID is reliable because common trends cannot be guaranteed. Therefore, this article will use Abadie SDID for further verification. The results are shown in Table 5. On indicators such as Healthy meal preparation methods, Non-processed food, Daily meal quantity, and Healthy food consumption, the coefficients before DID of the interaction term are all significantly positive, and the results are consistent with the previous article.

5.3.4 Competitive policy: exclusion of free medical examination program

Since 2009, China's national and local governments have successfully launched pilot policies on free physical examination programs. This policy aims to promote free physical examination services. The program covers urban and rural residents and provides comprehensive health check-ups, routine examinations, and joint disease screenings. The examination information is filled in the health examination form and included in the unified

TABLE 5 Abadie SDID regression results.

	HMPM (1)	NPF (2)	DMQ (3)	HFC (4)
DID	0.031***	0.021***	0.116***	0.080***
	(0.006)	(0.003)	(0.025)	(0.016)
Year FE	Control	Control	Control	Control
Household FE	Control	Control	Control	Control
R^2	0.234	0.891	0.877	0.870
Obs	40,739	40,739	40,739	40,739

***p < 0.01. Clustered robust standard errors at the household level are in parentheses.

management of individual health files. Then, the examination doctor must promptly inform the community of the evaluation results and provide free corresponding health guidance and management. The implementation of the free physical examination program coincides with the implementation of the LTCI pilot policy, so it is necessary to isolate the impact of the free physical examination program on household consumption behavior. We added the year of implementation of the free physical examination program policy and the pilot area (*FMEP*) interaction term in the model to control its impact on the main estimated results. It can be found from the estimation results that after controlling for the free physical examination program (see Table 6), the estimated coefficients of $LTCI_i \times Post_t$ are still significantly positive, which shows, to a certain extent, that the LTCI policy has a noticeable effect on increasing healthy food consumption.

5.3.5 Competitive policy: exclusion of pharmaceutical price negotiations

Sichuan, Shandong, and Jiangsu implemented pilot drug price negotiations in 2010, 2012, and 2013, respectively. Pharmaceutical price negotiations may indirectly affect healthy food consumption, especially regarding chronic disease treatment. The policy aims to bring drug prices down and reduce the financial burden on individuals when purchasing drugs, thus freeing up more disposable income. This increases people's spending on healthy foods as they can now spend more on healthier foods. Furthermore, success in pharmaceutical price negotiations may draw public attention to the healthcare system and drug pricing. This may increase people's awareness of health issues and prompt them to pay more attention to their health. In this case, people may buy more healthy foods to improve eating habits, enhance immunity, etc. The implementation of pharmaceutical price negotiations happens to be during the implementation period of the LTCI pilot policy, so it is necessary to isolate the impact of pharmaceutical price negotiations on household consumption behavior. We added the year of implementation of the pharmaceutical price negotiation policy and the interaction term of the pilot area (*PPN*) in the model to control its impact on the main estimation results. It can be found from the estimation results that after controlling for pharmaceutical price negotiations (see Table 7), the estimated coefficients of $LTCI_i \times Post_t$ are still significantly positive, indicating LTCI policy still has a robust effect on increasing healthy food consumption.

TABLE 6 A test of competitive policy: excluding the impact of free medical examination programs.

	HMPM (1)	NPF (2)	DMQ (3)	HFC (4)
$LTCI_i \times Post_t$	0.050***	0.030***	0.203***	0.181***
	(0.013)	(0.010)	(0.043)	(0.045)
FMEP	−0.109	−0.095	0.157	−0.391
	(0.077)	(0.101)	(0.138)	(0.473)
Gender	0.004	0.004**	−0.037	0.019*
	(0.014)	(0.002)	(0.038)	(0.010)
Birthplace	0.107**	0.033	−0.088	0.094
	(0.047)	(0.026)	(0.072)	(0.133)
Marry	0.007	0.000	0.036***	0.005
	(0.005)	(0.001)	(0.011)	(0.007)
Ethnic	0.038	−0.003	−0.047	0.006
	(0.030)	(0.005)	(0.086)	(0.024)
Income	−0.000	−0.000	0.002	−0.000
	(0.001)	(0.000)	(0.002)	(0.001)
Activity level	−0.008	0.000	0.138***	0.018
	(0.012)	(0.002)	(0.025)	(0.012)
Self-health evaluation	0.005	0.003***	0.085***	0.014**
	(0.008)	(0.001)	(0.017)	(0.006)
Medical history	0.017**	−0.001	0.018	0.003
	(0.008)	(0.003)	(0.017)	(0.013)
Tobacco and alcohol	0.008	−0.001	0.044***	−0.003
	(0.006)	(0.002)	(0.013)	(0.008)
Cleaning water	−0.003	0.027**	0.006	0.141**
	(0.017)	(0.012)	(0.042)	(0.057)
Home hygiene	0.004	0.001	0.039***	0.003
	(0.006)	(0.001)	(0.015)	(0.007)
Constant	0.516***	0.061***	1.732***	0.255***
	(0.024)	(0.004)	(0.061)	(0.020)
Year FE	Control	Control	Control	Control
Household FE	Control	Control	Control	Control
R^2	0.234	0.891	0.877	0.870
Obs	40,397	36,909	36,909	36,909

***p < 0.01, **p < 0.05, *p < 0.1. Clustered robust standard errors at the household level are in parentheses.

5.4 Discussion of heterogeneity

Figure 3 shows the difference in the impact of LTCI policies between urban and rural areas. The LTCI policy can better promote healthy food consumption among urban families. Generally, urban families have relatively higher income levels and better economic conditions (Min et al., 2021). LTCI policies can help urban families share the financial burden of caring for sick family members and

TABLE 7 A test of competitive policy: excluding the impact of pharmaceutical price negotiations.

	HMPM (1)	NPF (2)	DMQ (3)	HFC (4)
$LTCI_i \times Post_t$	0.058***	0.016**	0.066**	0.073***
	(0.013)	(0.005)	(0.033)	(0.014)
PPN	0.050	0.119***	0.570***	0.700***
	(0.034)	(0.038)	(0.136)	(0.177)
Gender	0.004	0.004*	−0.038	0.018*
	(0.014)	(0.002)	(0.038)	(0.009)
Birthplace	0.106**	0.034	−0.083	0.100
	(0.047)	(0.026)	(0.071)	(0.133)
Marry	0.007	0.000	0.035***	0.005
	(0.005)	(0.001)	(0.011)	(0.007)
Ethnic	0.038	−0.003	−0.044	0.008
	(0.030)	(0.005)	(0.086)	(0.024)
Income	−0.000	−0.000	0.002	−0.000
	(0.001)	(0.000)	(0.002)	(0.001)
Activity level	−0.008	0.000	0.136***	0.016
	(0.012)	(0.002)	(0.025)	(0.012)
Self-health evaluation	0.006	0.003***	0.085***	0.014**
	(0.008)	(0.001)	(0.017)	(0.006)
Medical history	0.017**	−0.000	0.019	0.004
	(0.008)	(0.003)	(0.017)	(0.013)
Tobacco and alcohol	0.008	−0.001	0.044***	−0.003
	(0.006)	(0.002)	(0.013)	(0.008)
Cleaning water	−0.001	0.027**	−0.005	0.139***
	(0.017)	(0.012)	(0.040)	(0.054)
Home hygiene	0.004	0.001	0.038**	0.002
	(0.006)	(0.001)	(0.015)	(0.007)
Constant	0.516***	0.061***	1.735***	0.258***
	(0.024)	(0.004)	(0.061)	(0.020)
Year FE	Control	Control	Control	Control
Household FE	Control	Control	Control	Control
R^2	0.234	0.891	0.877	0.871
Obs	40,397	36909	36909	36909

***p < 0.01, **p < 0.05, *p < 0.1. Clustered robust standard errors at the household level are in parentheses.

reduce financial pressure. This leaves urban households with more funds to spend on healthy food. In addition, urban residents generally pay more attention to health and quality of life. LTCI policies can remind people to pay attention to the health problems of family members and strengthen attention and emphasis on health. Urban households are more likely to be aware of the importance of food to health and are more inclined to purchase healthy foods. Urban areas generally have more healthy food supply channels, such as organic food stores, health supermarkets, etc. Implementing LTCI will likely promote the development of healthy food markets in urban areas further, providing a greater variety and better quality of healthy food options. Relative to rural areas, urban households prefer a convenient and fast lifestyle. LTCI policies can reduce the burden of caring for family members, allowing family members to spend more time and energy purchasing, preparing, and enjoying healthy foods. However, rural families may face financial challenges, especially after paying for long-term care, and they may not easily afford more expensive healthy food expenditures. Even if LTCI policies bring some economic support, this does not necessarily translate into more healthy food consumption. Moreover, rural households may be more inclined to spend their limited economic resources on obtaining primary health care services rather than purchasing more expensive healthy foods.

Differences in household size also have heterogeneous effects. This study will conduct group estimates based on the number of family members. Those with ≤2 family members form a group, and those with more than two form a group. Figure 4 shows that LTCI policies can promote healthy food consumption among larger households. The opposite behavior occurs only in healthy meal preparation methods. Generally speaking, a family with more people needs more food, and its economic expenditure is relatively higher. The LTCI policy can provide these families with financial support and help them bear higher food expenditures. Therefore, these households may be more likely to purchase healthier foods to ensure the nutritional needs of family members (Liu C. et al., 2021). Moreover, in larger families, there may be elderly or sick members who require long-term care. Long-term care insurance policies can provide these families with necessary care services and support, including dietary adjustments, nutritional supplements, etc. (Steeves et al., 2020). In this case, family members are likelier to choose healthy foods to meet caregiving needs. In larger households, family members may pay attention to each other and influence food choices (Liu C. et al., 2021). When the number of people is small, the LTCI policy increases healthy meal preparation methods. This may be related to the convenience of healthy meal preparation methods. With a small number of people, they will spend less time on complicated cooking methods. Additionally, smaller families may face more significant financial pressure because they cannot achieve the same savings in food costs as larger families through economies of scale (Deaton and Paxson, 1998). Moreover, smaller families may be more limited and inclined to spend their limited economic resources on basic living rather than purchasing more expensive healthy foods. LTCI policy does not directly address families' food expenditures. Finally, food storage and waste may be a bigger problem for smaller families, as they may not be able to effectively take advantage of buying food in bulk. Therefore, smaller families will not increase their food expenditures much.

The nature of a household member's work unit may also be an essential factor influencing healthy food consumption. This study will use group estimates based on the categories of family members' work units according to CHNS statistics. We divide the work units into government agencies, state-owned

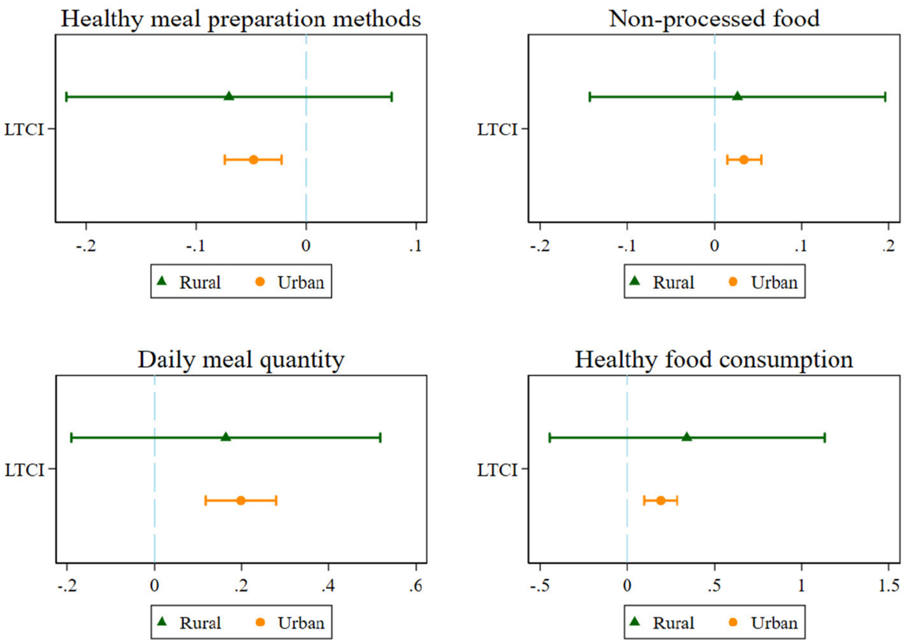

FIGURE 3
Urban-rural heterogeneity estimation results.

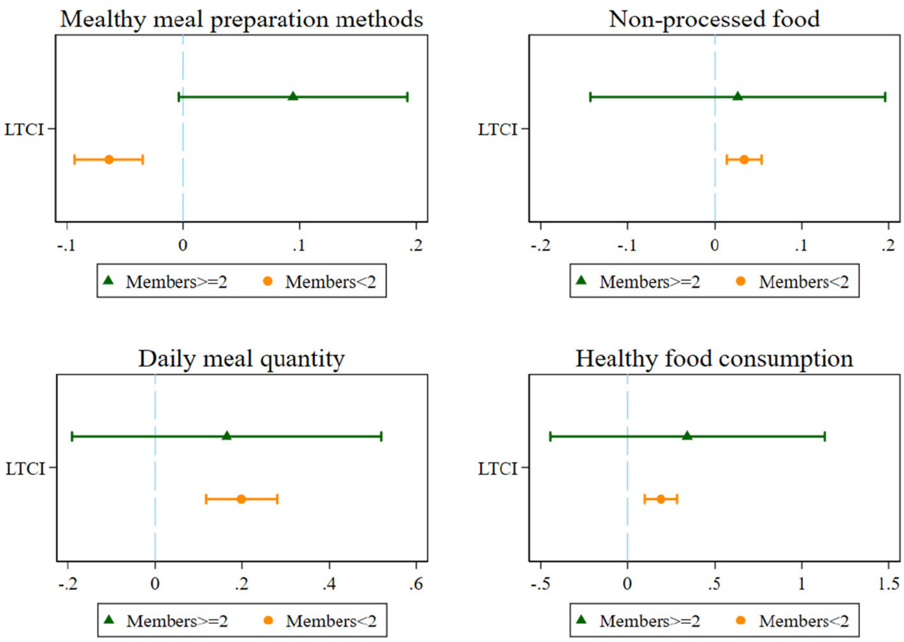

FIGURE 4
Family size heterogeneity estimation results.

institutions, research institutes, state-owned enterprises, and collective enterprises into the state-owned unit group (SOE), and the rest are classified into the private enterprise group (Non-SOE). The results in Figure 5 show that different unit categories will affect the effect of the LTCI policy on healthy food consumption. Among them, the LTCI policy is more able to promote healthy food consumption among households working in private enterprises. Families working in private enterprises usually do not have stable job security and generous benefits like those in state-owned enterprises (Ma et al., 2023a), so they pay more

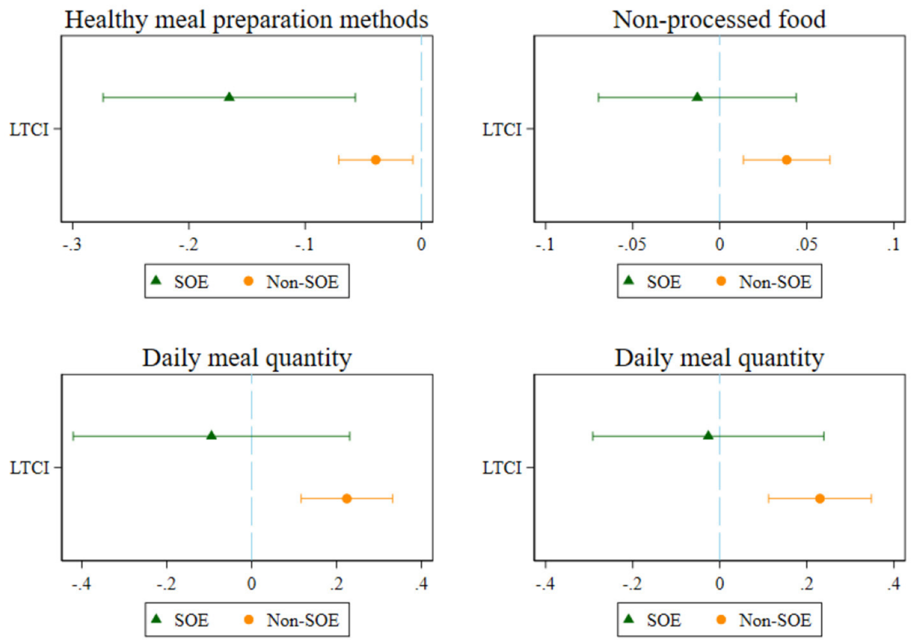

FIGURE 5
Work unit type heterogeneity estimation results.

attention to their health and welfare than their families. In this case, an LTCI policy can provide them with financial support to cope with the long-term illness and care needs that family members may face, thereby alleviating their financial pressure. This reduced financial stress can make them more likely to purchase more healthy foods to keep their families healthy. On the contrary, families working in state-owned enterprises usually have relatively stable job security and better welfare benefits (Serrano-Alarcón et al., 2022; Ma et al., 2023a), so they may pay more attention to other aspects of consumption, such as travel or entertainment. At the same time, the welfare benefits in state-owned enterprises are usually more generous than those in private enterprises, and they may pay less attention to the financial support provided by LTCI policies. On top of that, cultural and social factors further shape consumer behavior in these contexts (Wang et al., 2021). In the private sector, cultural values emphasizing individualism, materialism, and consumerism may drive higher consumption levels as individuals seek to express their identity and status through purchases. Social factors such as peer influence, media advertising, and lifestyle aspirations can also play an essential role in shaping consumption patterns in the private sector. In contrast, in state-owned enterprises, cultural values of collectivism, frugality, and social harmony may lead to more restrained consumption behavior (Bian et al., 2023). Social factors such as government campaigns to promote frugality, community norms emphasizing modesty, and concerns about sustainable resource use may influence individuals to prioritize the greater good over personal desires, leading to more conservative consumption choices.

6 Conclusions and implications

6.1 Conclusions

This study focuses on LTCI policies closely related to health consumption. We used CHNS data from 1989 to 2015 and adopted the DID analysis framework to examine the impact of changes in consumption behavior on healthy food consumption after households participated in the LTCI pilot. The results show that participation in LTCI policies can effectively increase healthy food consumption among Chinese households. This conclusion remains robust after parallel trend testing, placebo testing, and changing estimation methods. This conclusion adds to the existing literature on the impact of LTCI policies on healthy food consumption. Serrano-Alarcón et al. (2022) studied the impact of LTCI policy on household consumption and savings of the elderly. Recent literature discusses the effects of China's LTCI policy on household health consumption (Liu et al., 2023). However, many health food consumption-related issues regarding LTCI policy have not been well-discussed. These issues are essential for public health and wellbeing and understanding healthy food consumption preferences in consumer behavior. Our findings thus complement the missing literature on this point. Mechanism test shows that LTCI increases families' healthy diet preparation methods, daily meal consumption, and healthy food consumption structure through risk prevention mechanisms. After controlling for the Free Medical Examination Program and Pharmaceutical Price Negotiations, the estimated coefficients of LTCI are still significantly positive, indicating to a certain extent that the

LTCI policy still has a robust effect on increasing healthy food consumption. The heterogeneity test further proves that the LTCI policy can promote healthy food consumption among urban households. LTCI policies can also better promote healthy food consumption among larger households. Moreover, it is more likely to promote healthy food consumption among households working in the private sector.

6.2 Policy implications

The findings of this study have specific policy implications and practical significance for improving public health and increasing residents' healthy food consumption. First, carrying out LTCI can improve the preventive and rehabilitation care system from the social level, transform the public's medical needs into nursing needs, reduce unnecessary excessive medical treatment, and promote a daily healthy diet. The government should increase the publicity of LTCI, improve public awareness and understanding of LTCI, and encourage families to participate in LTCI to reduce the financial pressure faced by families due to illness and care needs while increasing the demand and consumption of healthy foods.

Secondly, the government should strengthen the popularization of healthy food knowledge among consumers and improve consumers' awareness and understanding of healthy food through publicity and education to better understand the importance of healthy food to physical health. Especially in rural areas, it is necessary to build healthy food supply channels, such as organic food stores, health supermarkets, etc.

Finally, the study's findings provide insights into specific factors that influence public health outcomes, such as access to health care, social determinants of health, and the impact of public health interventions. Policymakers can use this information to allocate resources more effectively, address the root causes of health disparities, and promote equitable access to health care. Additionally, findings may highlight the need for cross-sector collaboration and the integration of health considerations into non-health policies. Policymakers should work in areas as diverse as education, urban and rural planning, and economic development to develop holistic public health approaches that address the broader determinants of wellbeing.

6.3 Limitations

This study analyzes the relationship between consumer behavior and healthy food consumption, considering differences in demographic characteristics, socioeconomic status, and individual health levels. Nonetheless, this study has some limitations. Limited by data availability and the short duration of the LTCI pilot, only four provinces served as the experimental group in this study. Moreover, the geographical information of CHNS only reaches the provincial level. However, this study uses a variety of robustness tests, including weighting, to determine the credibility of the main results. However, this study cannot further analyze specific pilot cities or more detailed districts and counties. As time passes, more and more cities have begun pilot work on long-term care insurance, and more and more research databases have opened special questionnaires on LTCI. More high-quality empirical research on LTCI policies is expected in the future. Furthermore, future research should focus on assessing the scalability and sustainability of LTCI policies. Such research can help policymakers determine how to effectively implement and sustain LTCI policy interventions on a larger scale and ensure that LTCI has a positive and sustained impact on public health outcomes.

Data availability statement

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

Author contributions

WC: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. GM: Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing. ZJ: Formal analysis, Supervision, Writing – original draft, Writing – review & editing.

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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

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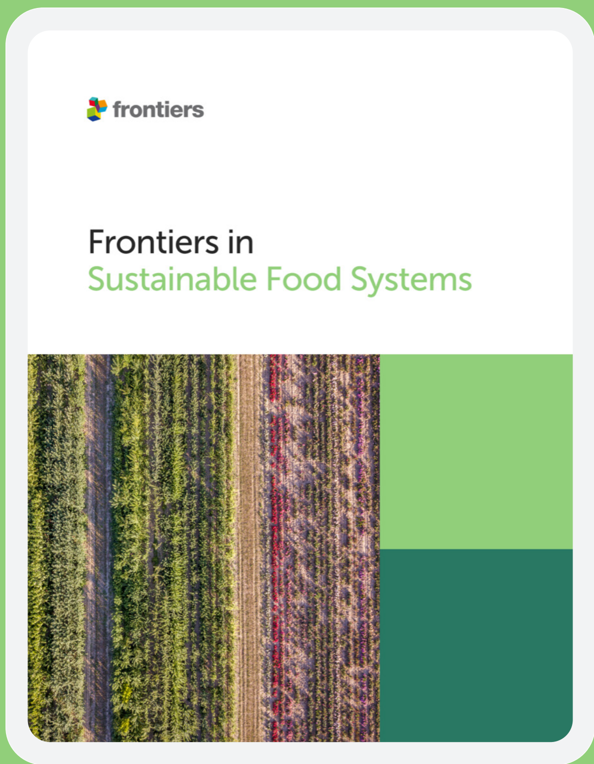

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