frontiers | Frontiers in Built Environment

TYPE Original Research
PUBLISHED 04 August 2025
DOI 10.3389/fbuil.2025.1646565

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OPEN ACCESS

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RECEIVED 13 June 2025
ACCEPTED 14 July 2025
PUBLISHED 04 August 2025

CITATION
Kiss NÉ, Nagy A and Tamás J (2025) Circular approach of greener broiler chicken production.
Front. Built Environ. 11:1646565.
doi: 10.3389/fbuil.2025.1646565

Circular approach of greener broiler chicken production

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The sustainability of agricultural production is a key issue, particularly in terms of fertilizer use, greenhouse gas emissions, and resource depletion. This study uses life cycle assessment (LCA) to compare the environmental impacts of composted and pelletized poultry manure (CPPL) and six different fertilizers (ammonium nitrate (AN), calcium ammonium nitrate (CAN), urea, monoammonium phosphate (MAP), triple superphosphate (TSP), and potassium chloride (KCl)) during corn and winter wheat production, as well as their impact on broiler chicken production. The study also took into account different fertilization methods and seasonal variations (summer and winter rotation), analyzing eleven environmental impact categories, including global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), abiotic resource use (abiotic depletion potential for elements (ADPe), abiotic depletion potential for fossil fuels (ADPf)), ozone layer depletion potential (ODP), photochemical oxidation potential (POP) and ecotoxicity potentials (freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP)). Based on the results, GWP was 11%–14% lower for CPPL production compared to fertilizers, while ADPf was 14%–56% lower. At the same time, AP was significantly higher for CPPL, mainly due to ammonia emissions. In crop production (corn, winter wheat), CPPL-based nutrient replenishment resulted in 11%–34% lower GWP and 14%–56% lower ADPf in most environmental scenarios compared to fertilizer treatments. In toxic impact categories (e.g., FAETP, MAETP), reductions of 3%–15% were observed. However, AP values were 2.6%–6.8% higher, and EP could be up to twice as high as for fertilizer treatments. In broiler chicken farming, when feed was produced from CPPL-grown crops, the environmental impact was 30%–85% lower in almost all categories examined than with fertilizer-based feed. Seasonal differences were moderate, with a 3%–5% increase in some categories during winter. Based on the results, CPPL offers a promising alternative to chemical fertilizers, especially in reducing greenhouse gas emissions and nutrient leaching. In line with circular economy principles, CPPL can contribute to the development of more sustainable agricultural systems.

KEYWORDS

life cycle assessment (LCA), CPPL, chemical fertilizers, maize, winter wheat, broiler chickens, sustainability, greenhouse gases

1 Introduction

Agriculture, as one of the largest resource-consuming sectors, generates significant environmental burdens, in particular through greenhouse gas (GHG) emissions, eutrophication and overuse of soil and water resources (FAO, 2020; Mrówczyńska-Kamińska et al., 2021; Singh et al., 2024). Under the European Green Deal, the European Union aims to make agricultural practices more sustainable, reduce the ecological footprint, while maintaining global food security. The EU's Farm to Fork Strategy considers reducing and improving the efficiency of synthetic inputs, in particular fertilisers and pesticides, and promoting organic alternatives as key elements (European Commission, 2020a; European Commission, 2020b; Montanarella, 2020; Šafář et al., 2022).

In order to achieve sustainability goals, the UN Sustainable Development Goals (SDGs) (United Nations, 2015) also emphasize the importance of sustainable consumption and production (SDG 12) and climate action (SDG 13). Making agricultural practices more environmentally sustainable, including the principles of circular economy, can contribute to achieving global sustainability goals while promoting more efficient and sustainable use of natural resources (Nwachukwu, 2023). The concept of a circular economy is based on waste minimization and material recycling, which is particularly important for sustainable agricultural production (Kalmykova et al., 2018; Soliwoda et al., 2020; Alava et al., 2022). By-products from animal husbandry, such as broiler chicken manure, can be used as organic fertilizers. Manure is converted into organic fertilizer through composting and granulation, which can improve soil fertility and reduce the use of chemical fertilizers. The use of organic fertilizers increases soil organic matter content, stimulates soil microbial activity, and can contribute to carbon sequestration in the long term (Bhowmik, 2021; Dagher et al., 2022; Badewa et al., 2023; Zhang L. et al., 2024).

Although the use of organic fertilizers has many advantages, it also has environmental impacts. During the decomposition of manure, significant amounts of ammonia, methane, and nitrous oxide (N_2O) can be released, which can increase the risk of acidification and eutrophication. In addition, the energy required for composting and granulation can also contribute to environmental impacts. In contrast, the production of chemical fertilizers is extremely energy-intensive and has significant environmental impacts. One of the most important steps in the production of nitrogen fertilizers is the Haber-Bosch process, which produces ammonia under high pressure and temperature. This process involves significant fossil energy consumption and emits large amounts of carbon dioxide (Sutton et al., 2011; Fernández–Hatzell, 2020; Lin et al., 2020). The production of phosphate and potash fertilizers also raises environmental concerns, particularly due to waste from phosphate mining and by-products from chemical processing (Farahani et al., 2024).

The life cycle assessment method can be used to quantify and evaluate the environmental impacts of individual processes. Life cycle assessment (LCA) is a methodology that allows the total environmental impact of a product or process to be tracked throughout its entire life cycle. LCA is particularly important for assessing the sustainability of agricultural systems, as it takes into account direct and indirect emissions related to production, raw material use, transport, and waste management. The method allows for the comparison of different manure management systems and their environmental impacts (International Organization for Standardization, 2006a; International Organization for Standardization, 2006b; Ormazábal et al., 2016; Notarnicola et al., 2017; Kiss et al., 2021; Kiss et al., 2022).

This research uses LCA to assess the environmental impacts of composted and granulated organic fertilizer (CPPL) from broiler chicken farming, comparing it with six different fertilizers (AN, CAN, urea, MAP, TSP, KCl). The study examines the use of fertilization systems in corn and wheat production and their impact on broiler chicken farming. The aim is to provide a comprehensive picture of the environmental impact of different nutrient supply strategies, including CPPL and six chemical fertilizers, taking into account the differences between summer and winter crop rotations and the feed-related effects on broiler production. The results can contribute to the development of more sustainable agricultural practices and the achievement of the objectives of the Farm to Fork strategy.

2 Materials and methods

2.1 Defining the goal and system boundaries of life cycle assessment

The three pillars on which the research is based (1. Intensive broiler chicken production, 2. Composting of broiler chicken manure followed by pellet production (Hosoya composting plant), 3. Crop production (maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.)) and the interrelationship between the three pillars are summarised in Figure 1.

The large amount of manure produced from broiler chickens is processed and recycled at the Hosoya composting plant. The CPPL produced is then used as a nutrient supplement to maximise the yield of crops, in this case maize and winter wheat.

The main focus of the analysis was the life cycle assessment of the material and energy flows during the production and use of CPPL.

However, the research could not be limited to the composting and granulation process in setting the system boundaries. In order to get a more accurate picture of the environmental impacts of CPPL production, broiler chicken production and crop production cannot be neglected.

The Hosoya composting plant processes and recycles large quantities of manure from broiler chickens, manure contaminated water from cleaning of the sheds and sludge from the slaughterhouse. These raw materials provide the main input stream for composting and granulation.

The crop production sector provides feed and litter for the broiler chicken farm. In this analysis, a life cycle assessment of

Abbreviations: LCA, Life Cycle Assessment; CPPL, Composted and Pelleted Poultry Litter; GWP, Global Warming Potential; AP, Acidification Potential; EP, Eutrophication Potential; ADPe, Abiotic Depletion Potential for Elements; ADPf, Abiotic Depletion Potential for Fossil Fuels; HTP, Human Toxicity Potential; TETP, Terrestrial Ecotoxicity Potential; MAETP, Marine Aquatic Ecotoxicity Potential; FAETP, Fresh Water Aquatic Ecotoxicity Potential; POP, Photochemical Oxidation Potential; ODP, Ozone Depletion Potential; AN, Ammonium Nitrate; CAN, Calcium Ammonium Nitrate; MAP, Monoammonium Phosphate; TSP, Triple Superphosphate; KCl, Potassium Chloride.

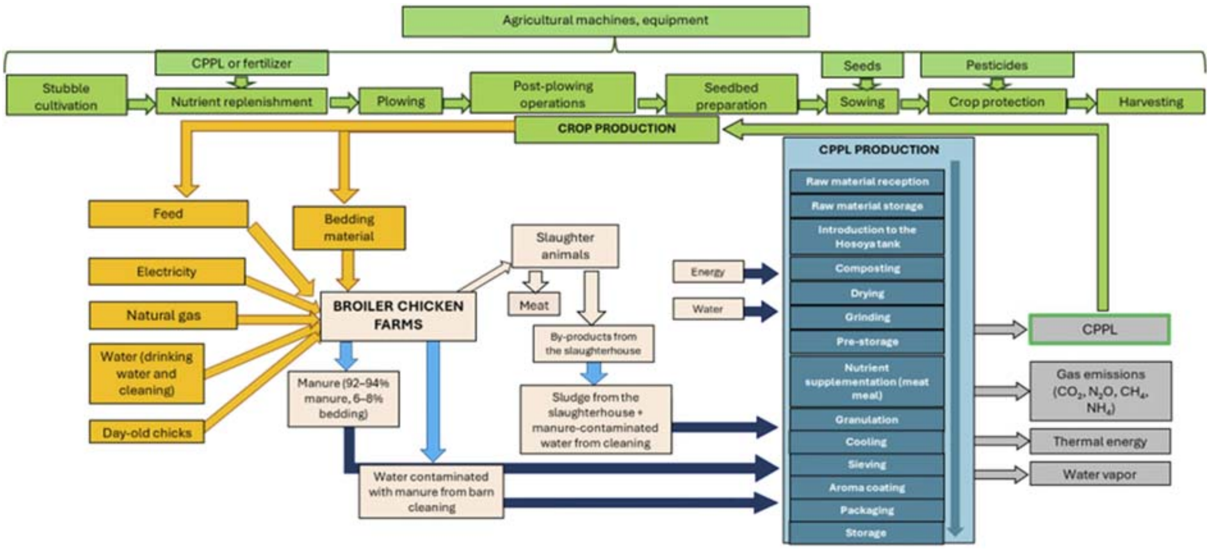

FIGURE 1
Systems of the circular economy.

TABLE 1 Input and output material and energy flows of one digester load and 1 kg of final product (CPPL).

Input material and energy flows	1 storage/Fermentor	1 kg final product (CPPL)
Poultry manure (mixed with sewage sludge, wet chicken manure, and water contaminated with poultry manure)	1,500 kg	1.338 kg
Water	150 L	0.067 L
Electricity (mixing, conveyors, grinders, sifters, etc.)	502.02 MJ	0.45 MJ
Fuel	130.5 MJ	0.087 MJ
Output material and energy flows		
Final product: composted pelletized poultry litter (CPPL)	~1,490 kg	1 kg
Emissions to air		
Ammonia (NH_4)	1.845 kg	0.0012 kg
Nitrous oxide (N_2O)	0.097 kg	0.00006 kg
Methane (CH_4)	0.156 kg	0.0001 kg

maize and winter wheat production was selected from among the as feed crops.

In the following paragraphs, the purpose of the analyses and the functional units are described separately, pillar by pillar.

2.1.1 The aim of the life cycle assessment of hosoya composting plant

The role of granulate as a potential alternative to fertilizers was evaluated by exploring, analyzing and comparing the environmental impacts. The analysis examined the environmental impacts of the production of granules in the Hosoya composting plant and the production of different fertilizers. The environmental impacts were determined for the following functional units.

a) Production of 1 kg of final product

The environmental impact of the production process was compared for the production of 1 kg of CPPL with the production of 1 kg of chemical fertilizer. The chemical fertilizers concerned included ammonium nitrate (AN), calcium ammonium nitrate (CAN), urea, triple superphosphate (TSP), monoammonium phosphate (MAP) and potassium chloride (KCl). The assessment covered only the life cycle of the processes in the plants, from the arrival of the raw material at the plant to the production and packaging of the final product.

(b) Production of 1 kg of active substance

The environmental impact analysis was carried out for 1 kg of N, P_2O_5 and K_2O content for both CPPL and fertilizers.

TABLE 2 Input and output material and energy flows of 1 ton maize and winter wheat production.

Input material and energy flows	1 t harvested maize	1 t harvested winter wheat
Stubble cultivation with shredder (h)	0.1	0.1
Fertilization with CPPL (h)	0.19	0.15
Fertilization with CPPL (kg)	208	212.27
Primary tillage: plowing (200 HP machine) (h)	0.84	0.7
Primary tillage finishing with harrow (h)	0.27	0.25
Seedbed preparation (h)	0.49	0.45
Sowing (h)	0.54	0.46
Crop protection: row cultivation (h)	0.16	0.10
Crop protection: chemical spraying (h)	0.10	0.16
Harvesting (h)	0.52	0.49
Seeds (kg)	21.28	19.25
Electricity consumption (irrigation, pesticide production, seed production) (kWh)	363.66	15.3
Natural gas consumption (m^3)	18.35	
Energy, gross calorific value (MJ)	12,953.69	15,393.49
Carbon dioxide sequestered in biomass (kg)	1,247.34	1,436.99
Water for irrigation (m^3)	643.75	0.44
Output material and energy flows		
Main product (t)	1	1
Emissions to air: CO2 (kg)	8.99	9.6
Emissions to air: NH3 (kg)	3.48	1.9
Emissions to air: N2O (kg)	1.15	0.62
Emissions to air: NOx (kg)	0.94	0.62
Emissions to soil: pesticide residues (kg)	1.01	0.28
Emissions to soil: heavy metals (Cd, Cr, Cu, Pb, Hg, Ni, Zn) (kg)	−25.79	−11.98
Emissions to groundwater: NO3 (kg)	52.61	19.02
Emissions to groundwater: PO4 (kg)	0.09	0.03
Emissions to groundwater: heavy metals (Cd, Cr, Cu, Pb, Hg, Ni, Zn) (kg)	9.71	5.53
Emissions to surface water: PO4 (kg)	0.3	0.07
Emissions to surface water: heavy metals (Cd, Cr, Cu, Pb, Hg, Ni, Zn) (kg)	22.66	10

2.1.2 The aim of the life cycle assessment of maize and winter wheat production

The aim was to determine and compare the environmental impacts of maize and winter wheat production. The LCA identified the critical points of the growing technology under CPPL (1.5 t/ha) based nutrient supplementation and different combinations of N, P and K fertilizers. The amount of fertilizers was determined in proportion to the N, P_2O_5 and K_2O content of CPPL.

TABLE 3 Input and output material and energy flows of broiler chicken production in the winter and summer period.

Input material and energy flows	Winter period	Summer period
Day-old chicks (pcs)	256,000	256,000
Feed (t)	1186.3	1169.4
Vitamins (kg)	98.5	128.0
Drinking water (t) (including cleaning)	3841.5	8689.4
Bedding (straw pellet) (t)	24.7	23.9
Electricity, low voltage (kWh)	39844.2	66275.1
Heating, natural gas (m^3)	69665.0	16538.8
Output material and energy flows		
Delivered chickens (pcs)	244,473	243,189
Delivered chickens (t)	619.41	610.57
Manure (t)	102.1	111.5
Technological wastewater (t)	102.9	104.0
Ammonia (NH_3) (t)	3.77	3.71
Methane (CH_4) (t)	0.53	0.52
Nitrous oxide (N_2O) (t)	4.04	3.98
Nitrogen oxides (NO_x) (t)	0.04	0.04

2.1.3 The aim of the life cycle assessment of broiler production

The input and output material and energy flows required for broiler chicken production in the summer (April to September) and winter (October to March) rotation periods were collected separately. The aim was to determine the environmental critical points per 1 ton live weight of broiler chickens in the summer and winter months.

2.2 Life cycle inventory analysis

2.2.1 Life cycle inventory analysis of the hosoya composting plant

The life cycle inventory analysis examines the relevant material and energy flows required to produce CPPL (composted chicken manure pellets). The data presented below in Table 1 Refer to one digester load and 1 kg of final product.

The analysis is focused only on the input and output material and energy flows, the relevant data are derived from information provided by the plant and from the OpenLCA software calculation.

To assess the robustness of the life cycle inventory data and the potential variability of environmental impacts, a sensitivity analysis was designed. The input parameters of the CPPL production process (poultry manure, water, electricity, and fuel consumption) were varied by ±20%. These variations allow the evaluation of how sensitive key impact categories (e.g., GWP, AP, ADPf) are to the assumed input values. The results of the sensitivity analysis are discussed in Results and discussion.

2.2.2 Life cycle inventory analysis of the maize and winter wheat production

The life cycle inventory analysis examined the cultivation of maize and winter wheat for the production of 1 tonne of harvested crop (Table 2). The description of material and energy flows includes the machinery and inputs required for field operations and the associated energy and material use, in the case where nutrient replenishment was done by CPPL. The inventory includes field operations such as tilling, fertilising, base cultivation, seedbed preparation, sowing, crop protection and harvesting. Inputs include seeds, CPPL and plant protection products, as well as the energy use related to their production and use. The calculations are based on data from the Agribalyse database, which gives the field processes in units of time (hours) and calculates the material and energy flows. The analysis also took into account emissions from fuel combustion.

The temporal boundary of the assessment is "harvest to harvest", i.e., it does not take into account post-harvest processes such as drying or storage, even if they take place within the farm's territory.

The maize was grown under irrigated conditions, as the sample farm and a related farm supplying fodder crops also grow maize under irrigated conditions. For winter wheat, minimal water demand was

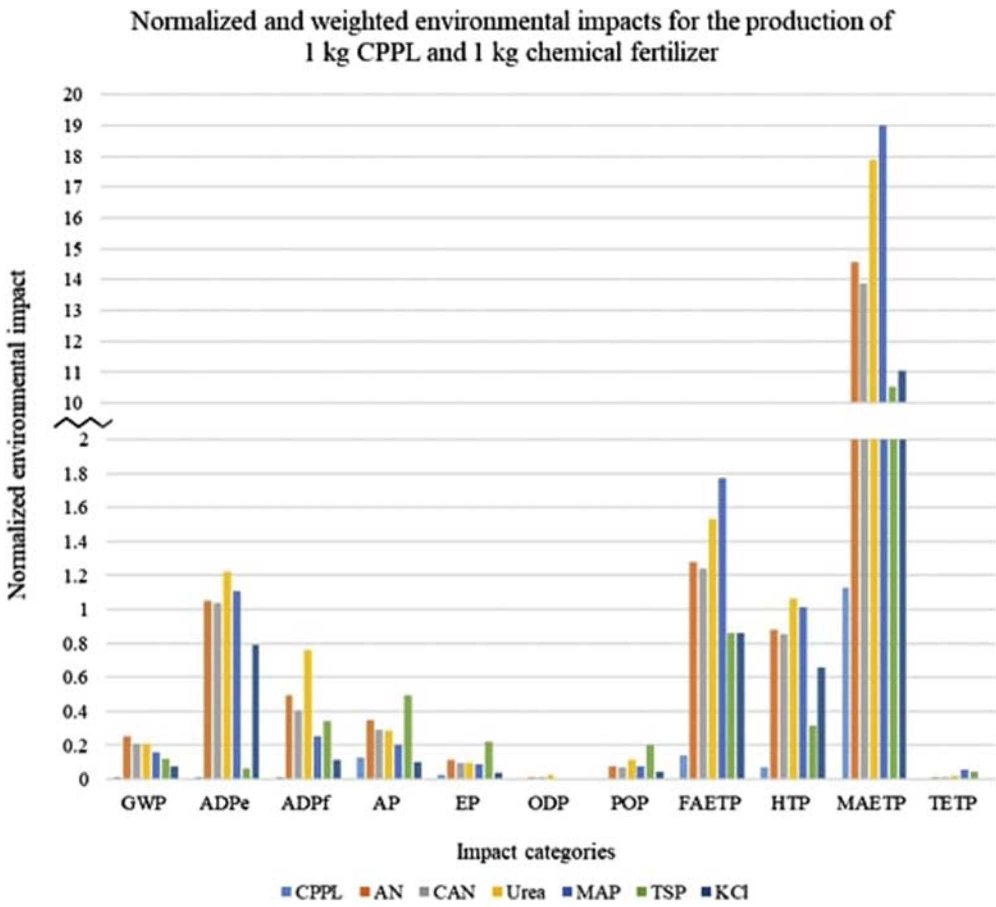

FIGURE 2
Normalized and weighted values for the production of 1 kg CPPL and 1–1 kg chemical fertilizer (CML-IA baseline, EU25 + 3, 2000). ADPe, Abiotic Depletion Potential of Elements; ADPf, Abiotic Depletion Potential of Fossil Fuels; AP, Acidification Potential; EP, Eutrophication Potential; GWP, Global Warming Potential; ODP, Ozone Depletion Potential; POP, Photochemical Oxidation Potential; FAETP, Freshwater Aquatic Ecotoxicity Potential; HTP, Human Toxicity Potential; MAETP, Marine Aquatic Ecotoxicity Potential; TETP, Terrestrial Ecotoxicity Potential.

expected. The energy use and emissions of the two crops are different due to different cultivation technology requirements.

Negative values are observed for emissions to soil, indicating that the uptake of heavy metals by the plants exceeds the amount released to the soil. This is particularly the case when large amounts of biomass are harvested. Negative values may also be due to emissions from leaching and erosion. Such phenomena are not uncommon in life cycle analyses and often occur due to multifunctional processes or differences between data systems.

2.2.3 Life cycle inventory analysis of broiler chicken production

Input and output material and energy flows in broiler chicken production were analysed on the basis of winter and summer rotations. The data for the study was provided by a Hungarian company, Baromfi-Coop Kft. And was completed based on the single environmental permit of the farm. The analysis focused on the consumption of day-old chicks, feed, drinking water, litter, energy (heating and ventilation) and the outputs at the end of the rotations (Table 3).

The data were analysed using OpenLCA software and the results were calculated on a per 1 tonne live weight basis for comparison with literature data. The study only covered the transport of day-old chicks and feed to the farm.

2.3 Life cycle impact assessment

The analyses were carried out using OpenLCA software, which provides a complete set of data for analysing material and energy flows. The French Agribalyse database was used to carry out the analyses, which is provides a large amount of data for the necessary analyses (Colomb et al., 2015; Koch and Salou 2020; Asselin-Balençon et al., 2020).

Based on Kiss et al. (2021), the environmental assessment covered eleven impact categories: abiotic depletion potential for elements (ADPe), abiotic depletion potential for fossil fuels (ADPf), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), photochemical oxidation potential (POP), freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), and terrestrial ecotoxicity potential (TETP).

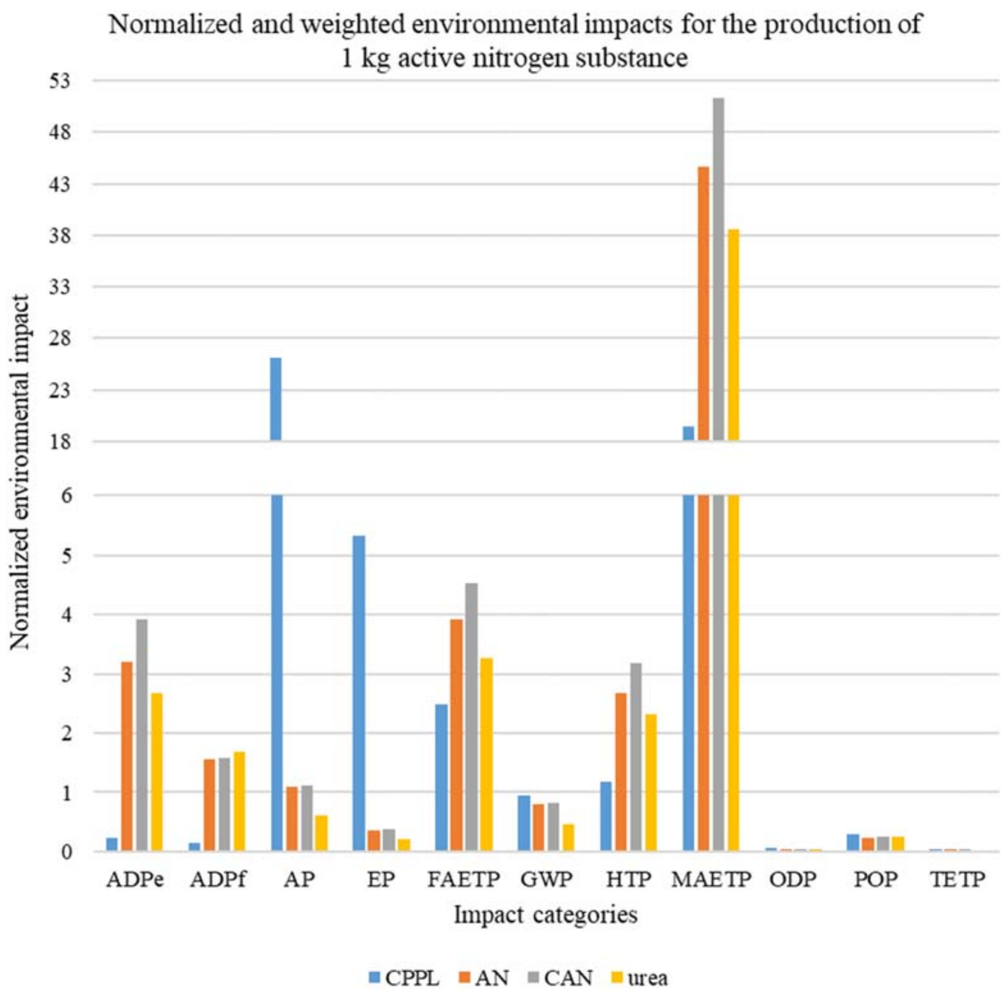

FIGURE 3
Normalized and weighted environmental impacts for the production of 1 kg active nitrogen substance (CML-IA baseline, EU25 + 3, 2000). (CML-IA baseline, EU25 + 3, 2000). ADPe, Abiotic Depletion Potential of Elements; ADPf, Abiotic Depletion Potential of Fossil Fuels; AP, Acidification Potential; EP, Eutrophication Potential; GWP, Global Warming Potential; ODP, Ozone Depletion Potential; POP, Photochemical Oxidation Potential; FAETP, Freshwater Aquatic Ecotoxicity Potential; HTP, Human Toxicity Potential; MAETP, Marine Aquatic Ecotoxicity Potential; TETP, Terrestrial Ecotoxicity Potential.

3 Results and discussion

3.1 Environmental impacts of CPPL and chemical fertilizers production

Figure 2 Shows the results of the impact assessment step, where the environmental burden was determined for 1 kg CPPL and 1 kg of each chemical fertilizer (AN, CAN, urea, MAP, TSP, KCl). Based on the results of Figure 2, it can be stated that the values per 1 kg of CPPL were lower in all 11 impact categories with one exception (AP for KCl).

The results show that the MAETP of the six fertilizers tested is extremely high, especially for MAP fertilizer, compared to the other impact categories (10.539–17.891 ng). The high value of MAETP in NPK fertilizers can be explained by the fact that heavy metals (e.g., cadmium, lead) and other toxic by-products from industrial processing pollute marine ecosystems (Hasan et al., 2017; Mishra et al., 2018; Ali et al., 2019; El-Hassanin et al., 2022; Onyena & Nwaogbe, 2024). After MAETP, the most significant impact categories for fertilizers are FAETP (0.903–1.73 ng) (because of phosphate and nitrate leaching), ADPe (except TSP between 0.79–1.23 ng) and HTP (0.343–1.07 ng).

For CPPL, the most significant impact categories are AP (1.43 ng) and MAETP (1.07 ng), which are the most significant contributors to the environmental burden.

The lower values for CPPL can also be explained by the fact that the production of CPPL is based on composting and pelleting processes, which mainly require electrical energy but do not involve significant industrial synthesis or fossil energy use. In contrast, the production of NPK fertilizers is based on energy-intensive chemical reactions, in particular the Haber-Bosch process, which produces ammonia at high pressure and temperature (Wang et al., 2019; Fernández–Hatzell, 2020; Lin et al., 2020). In the case of phosphorus and potassium fertilizers, the mining and processing of phosphate and potassium-containing mineral raw materials is also energy-intensive and has a significant environmental impact (Ouikhalfan et al., 2022; Bertau et al., 2024).

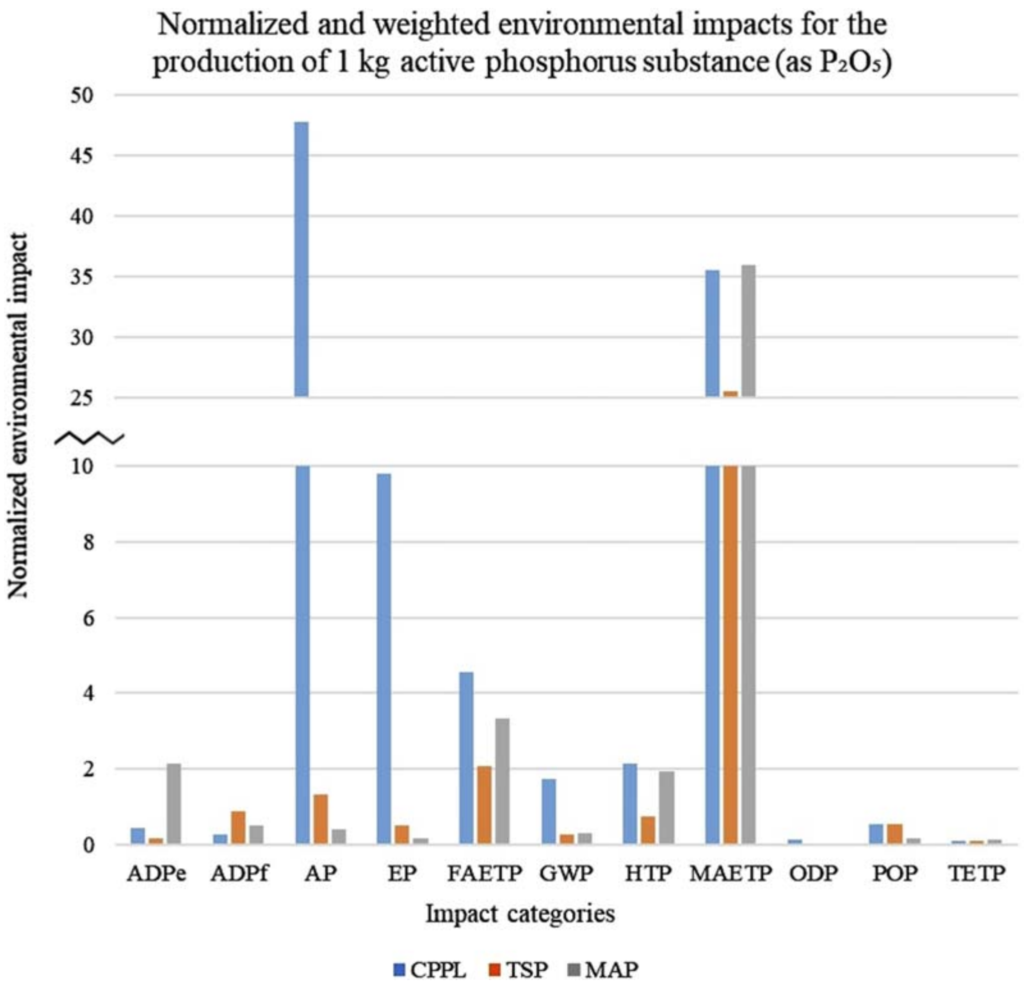

FIGURE 4
Normalized and weighted environmental impacts for the production of 1 kg active phosphorus substance (as P_2O_5) (CML-IA baseline, EU25 + 3, 2000). ADPe = Abiotic Depletion Potential of Elements; ADPf, Abiotic Depletion Potential of Fossil Fuels; AP, Acidification Potential; EP, Eutrophication Potential; GWP, Global Warming Potential; ODP, Ozone Depletion Potential; POP, Photochemical Oxidation Potential; FAETP, Freshwater Aquatic Ecotoxicity Potential; HTP, Human Toxicity Potential; MAETP, Marine Aquatic Ecotoxicity Potential; TETP, Terrestrial Ecotoxicity Potential.

In terms of atmospheric emissions and impacts, the use of NPK fertilizers is associated with significant emissions of N_2O, which is 298 times more powerful greenhouse gas than CO_2. (Wang et al., 2021; Slameto et al., 2024). In contrast, ammonia (NH_3) emissions are higher for CPPL due to the formation of ammonia during the decomposition of organic matter from animal manure, which increases the AP (Aneja et al., 2020; Owens et al., 2020).

For NPK fertilizers, it can also be said that the nitrate and phosphate content leached to water is higher, contributing to eutrophication potential (EP) (Bartoszewicz and Karp, 2012; Elekhtyar and AL-Huqail, 2023). While for CPPL, the degradation is more gradual, so nitrogen and phosphorus are mobilized more slowly, reducing the risk of rapid water pollution.

After the environmental burden of 1–1 kg of the final product, the environmental impact of 1 kg of the active substance was determined. For the N-substance, in addition to CPPL, AN, CAN and urea chemical fertilizers were also included in the impact assessment (Figure 3).

On a per kg N-active substance basis, CPLL showed lower environmental burdens for ADPe, ADPf, FAETP, HTP and MAETP.

For chemical fertilizers, the highest impact category was MAETP (38.6 - 51.31 ng), followed by FAETP (3.26 - 4.53 ng). These high values are attributed to the intensive chemical processes involved in the production of nitrogen fertilizers, in particular the Haber-Bosch process, which is highly energy intensive and produces significant by-product emissions that are detrimental to aquatic ecosystems. Also showing values closer to FAETP are the ADPe (2.68 - 3.91 ng) and the HTP (2.32 - 3.18 ng). For ADPe, nitrogen fertilizers show higher values than CPPL. This is due to the fact that the production of chemical fertilizers relies heavily on non-renewable resources such as phosphate rock and natural gas, which are needed to produce the ammonia and phosphate components (Arora et al., 2016; Lucentini et al., 2021; Fernández et al., 2024). In the case of HTP, values are increased by emissions of ammonia, sulphur dioxide and other toxic by-products generated during chemical synthesis and processing.

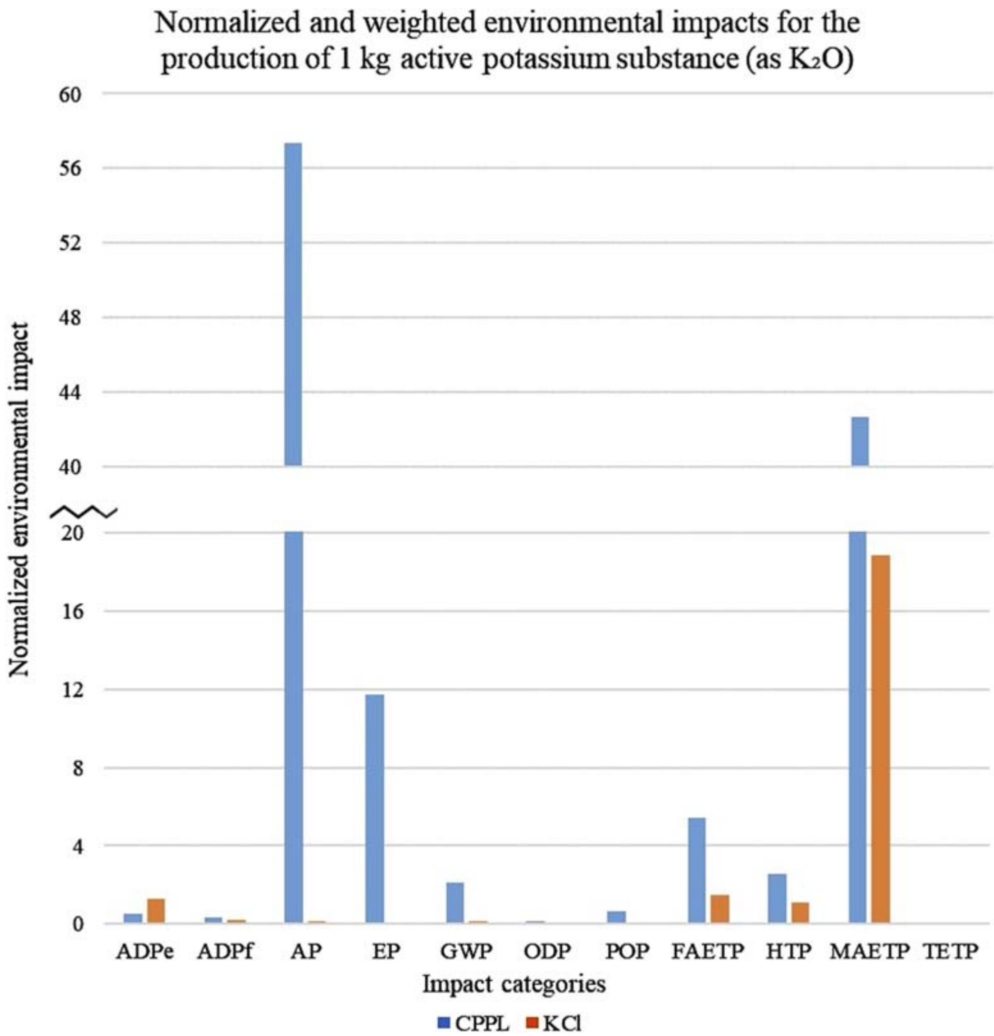

FIGURE 5
Normalized and weighted environmental impacts for the production of 1 kg active potassium substance (as K_2O) (CML-IA baseline, EU25 + 3, 2000). ADPe, Abiotic Depletion Potential of Elements; ADPf, Abiotic Depletion Potential of Fossil Fuels; AP, Acidification Potential; EP, Eutrophication Potential; GWP, Global Warming Potential; ODP, Ozone Depletion Potential; POP, Photochemical Oxidation Potential; FAETP, Freshwater Aquatic Ecotoxicity Potential; HTP, Human Toxicity Potential; MAETP, Marine Aquatic Ecotoxicity Potential; TETP, Terrestrial Ecotoxicity Potential.

In the case of CPPL, the MAETP (19.4 ng) was only the second highest impact category (due to the high electricity consumption of the pelleting process), the first being the AP (26.06 ng), which is many times higher than the AP observed for chemical fertilizers. This high result is due to the emission of ammonia, which is produced during the decomposition of organic matter and during fertilization. The third highest value was observed for EP (5.34 ng), which is also mainly due to the decomposition of organic matter (Hotta et al., 2007; Guardia et al., 2010; Salimin, 2011).

Figure 4 Shows the normalized and weighted values obtained for each impact category for 1 kg of P_2O_5.

For CPPL, AP represents the most significant impact category (47.78 ng). Its value is several times higher than that of chemical fertilizers (TSP: 1.31 ng, MAP: 0.39 ng). This result is mainly attributed to the decomposition of animal manure.

The second highest value for CPPL (the first for phosphorus fertilizers) is MAETP. For CPPL and MAP, the MAETP is similarly high (35.56 ng and 36.01 ng), while for TSP it is slightly lower (25.54 ng). For CPPL, this is probably due to indirect emissions from high electrical energy use leading to the release of pollutants. CPPL also has a high EP (9.79 ng), which is significantly higher than that of phosphorus fertilizers (TSP: 0.49 ng, MAP: 0.17 ng). This high value is due to the leaching of organic nitrogen and phosphorus in CPPL, which may lead to eutrophication of aquatic ecosystems (Torstensson et al., 2006; Sørensen–Rubæk, 2011; Hu et al., 2024).

The ADPf is higher for both TSP and MAP fertilizers than for CPPL because of the intensive energy use in their production, which is covered by fossil fuels. In contrast, the use of fossil energy in the production of CPPL is lower because the energy demand for pelletisation and composting is lower compared to the chemical processing of phosphorus fertilizers (Sarlaki et al., 2021; Furuhashi et al., 2024; Cwalina et al., 2025). MAP also has higher ADPe, MAETP and TETP compared to CPPL, which are also related to energy and raw material requirements.

Figure 5 Shows the normalized and weighted values obtained for each impact category for 1 kg of K_2O.

The results show that the environmental burden of CPPL and KCl during the production of 1 kg of K_2O-substance differs significantly for different impact categories. For CPPL, the AP (57.34 ng), the EP (11.75 ng) and MAETP (42.68 ng) are particularly high, whereas for KCl the highest load is the MAETP (18.84 ng), but this is also significantly lower than for CPPL. Mining and subsequent chemical purification is one of the most environmentally damaging processes in the production of KCl. This activity is mainly reflected in the MAETP, but KCl does not contribute significantly to acidification and eutrophication, as potassium fertilizers do not contain nitrogen and their phosphorus content is negligible (Jaskulska et al., 2014; Antoniadis et al., 2015).

To ensure the robustness of the life cycle assessment results, a sensitivity analysis was conducted in line with ISO 14040 (2006) recommendations. Sensitivity analysis is a widely applied method in LCA to assess the reliability and variability of results under input uncertainty (Kulczycka et al., 2015). It is particularly relevant in agricultural and waste management systems, where operational conditions can fluctuate, as also noted in recent studies focusing on the treatment of organic waste and agri-environmental systems (Kim et al., 2022; Kaddoura et al., 2025). By identifying the most responsive parameters, this method supports more targeted sustainability improvements and more confident decision-making in circular agricultural practices. In this case the analysis focused on the CPPL production system, by modifying key input parameters such as electricity and fuel consumption—two major contributors to environmental load. Results indicated that the most sensitive impact categories were GWP and ADPf. A 10% increase or decrease in these inputs resulted in a 7%–11% variation in the total environmental load for these categories. This highlights that energy efficiency and optimization in composting operations are critical intervention points for reducing the environmental footprint of CPPL-based fertilization.

In summary, these findings suggest that in the field of fertilizer manufacturing, CPPL is environmentally more favourable than chemical fertilizers, except for the AP, which is higher due to ammonia emissions. According to results, the use of CPPL can significantly reduce fossil resource use (ADPf), greenhouse gas emissions (GWP), depletion of abiotic elements (ADPe), and the burden on marine and freshwater ecosystems (MAETP, FAETP). For nitrogen-based fertilization (AN, CAN, urea), CPPL is particularly advantageous, as the production of synthetic nitrogen fertilizers is energy-intensive. For phosphorus- (MAP, TSP) and potassium-based (KCl) fertilization, the use of CPPL can reduce the depletion of mineral resources, but it can also lead to higher EP and AP, which can be reduced by appropriate application strategies.

3.2 Environmental impact of fertilization methods in maize and wheat production

3.2.1 Environmental impact of fertilization methods in maize production

In the crop production scenario, in addition to CPPL, various NPK fertilizer combinations were created (Table 4). The selected combinations allowed for a comprehensive assessment of how different NPK formulations influence environmental performance in crop production.

TABLE 4 Composition of NPK fertilizer combinations.

NPK combination	Composition
NPK1	AN + TSP + KCl
NPK2	AN + MAP + KCl
NPK3	CAN + TSP + KCl
NPK4	CAN + MAP + KCl
NPK5	Urea + TSP + KCl
NPK6	Urea + MAP + KCl

The analysis of Table 5 Shows that the different fertilization methods have a significant impact on the environmental impact of maize cultivation. CPPL fertilization generally results in lower environmental impacts, while different chemical fertilizer combinations NPK1-NPK6 show different impacts in different categories.

In terms of ADPe and ADPf, the CPPL method shows the lowest values (ADPe: 0.253, ADPf: 0.138), while the chemical fertilizer treatments show higher values. The value of ADPe is highest for CAN-based fertilization methods (NPK3 and NPK4) (0.310 and 0.308), while AN based fertilization (NPK1 and NPK2) shows higher values for ADPf (0.159 and 0.155). This suggests that CAN and AN based fertilizers are more resource intensive to produce.

For the AP, the CPPL method shows a significantly lower value (0.538), while for chemical fertilizer treatments these values range between 0.898 and 0.908. The AN-based fertilization treatments (NPK1 and NPK2) have the highest AP (0.908 and 0.902), which is related to acidification processes resulting from the degradation of ammonium nitrate (Tkaczyk et al., 2020; Kumar et al., 2024).

For the EP, CPPL (0.474) also shows a lower effect than chemical fertilizer combinations, with values ranging from 0.563 to 0.565. CAN-based fertilization (NPK3 and NPK4) shows the highest EP (0.565 and 0.563), which may be due to nitrate and phosphate leaching.

In terms of GWP, the CPPL method shows significantly more favourable values (0.124) than chemical fertilizer treatments, which show values between 0.177 and 0.187. Urea-based fertilizers (NPK5 and NPK6) have the highest GWP values (0.187 and 0.186), probably due to nitrous oxide (N_2O) emissions from decomposition in the soil.

Minimal differences in ODP were observed between CPPL and chemical fertilizer-based combinations (0.015–0.016), suggesting that this impact category is less dependent on the fertilization method.

For POP, CPPL (0.0411) shows slightly lower values than NPK fertilizers (0.0437–0.0461). AN-based fertilization methods (NPK1 and NPK2) have the highest POP values (0.0459 and 0.0437), which may be related to the emission of oxidants.

The CPPL in the ecotoxicity potential categories (FAETP, HTP, MAETP, TETP) generally show lower values, except for the MAETP, where the differences are smaller. The FAETP and HTP values for CPPL are 0.843 and 0.606, respectively, while for NPK fertilizers they are slightly higher (0.877-0.889 and 0.636-0.645, respectively). The MAETP values are higher for all

TABLE 5 Normalized and weighted values for the production of maize (CML-IA baseline, EU25 + 3, 2000).

Impact categories	CPPL	NPK1	NPK2	NPK3	NPK4	NPK5	NPK6
ADPe	0.253	0.294	0.302	0.301	0.310	0.289	0.297
ADPf	0.138	0.159	0.155	0.159	0.156	0.161	0.156
AP	0.538	0.908	0.902	0.908	0.903	0.903	0.898
EP	0.474	0.565	0.563	0.565	0.563	0.564	0.561
GWP	0.124	0.178	0.177	0.178	0.178	0.187	0.187
ODP	0.0152	0.0151	0.0150	0.0151	0.0150	0.0151	0.0150
POP	0.0411	0.0459	0.0437	0.0460	0.0439	0.0461	0.0438
FAETP	0.843	0.877	0.881	0.884	0.889	0.871	0.874
HTP	0.606	0.636	0.640	0.641	0.645	0.632	0.636
MAETP	3.609	4.118	4.141	4.191	4.223	4.062	4.079
TETP	0.0198	0.0203	0.0203	0.0204	0.0204	0.0202	0.0203
Total	6.6611	7.8163	7.84	7.9085	7.9463	7.7504	7.7671

ADPe, Abiotic Depletion Potential of Elements; ADPf, Abiotic Depletion Potential of Fossil Fuels; AP, acidification potential; EP, eutrophication potential; GWP, global warming potential; ODP, ozone depletion potential; POP, photochemical oxidation potential; FAETP, freshwater aquatic ecotoxicity potential; HTP, human toxicity potential; MAETP, marine aquatic ecotoxicity potential; TETP, terrestrial ecotoxicity potential.

TABLE 6 Normalized and weighted values for the production of winter wheat (CML-IA baseline, EU25 + 3, 2000).

Impact categories	CPPL	NPK1	NPK2	NPK3	NPK4	NPK5	NPK6
ADPe	0.074	0.109	0.117	0.115	0.122	0.105	0.111
ADPf	0.022	0.040	0.036	0.039	0.036	0.041	0.037
AP	0.250	0.244	0.238	0.243	0.238	0.239	0.234
EP	0.181	0.182	0.179	0.182	0.180	0.180	0.178
GWP	0.0449	0.0520	0.0513	0.0519	0.0515	0.0509	0.0503
ODP	0.0019	0.0018	0.0017	0.0018	0.0017	0.0018	0.0017
POP	0.007	0.011	0.009	0.011	0.009	0.011	0.009
FAETP	0.919	0.948	0.953	0.955	0.960	0.944	0.947
HTP	0.090	0.113	0.117	0.117	0.123	0.110	0.113
MAETP	0.658	1.092	1.124	1.161	1.198	1.060	1.068
TETP	0.670	0.670	0.671	0.671	0.671	0.670	0.670
Total	2.9178	3.4628	3.497	3.5477	3.5902	3.4127	3.419

ADPe, Abiotic Depletion Potential of Elements; ADPf, Abiotic Depletion Potential of Fossil Fuels; AP, acidification potential; EP, eutrophication potential; GWP, global warming potential; ODP, ozone depletion potential; POP, photochemical oxidation potential; FAETP, freshwater aquatic ecotoxicity potential; HTP, human toxicity potential; MAETP, marine aquatic ecotoxicity potential; TETP, terrestrial ecotoxicity potential.

fertilizer treatments (4.079–4.223), while the CPPL is 3.609, which may indicate that fertilizer application methods have a significant impact on marine ecosystems.

Overall, the CPPL fertilization method seems to be a more environmentally friendly alternative compared to chemical fertilizer-based treatments, especially in terms of

AP, EP and GWP. The different fertilization methods show different environmental impacts: AN-based fertilization increases acidification (David et al., 2014), CAN-based fertilization increases eutrophication (Torstensson et al., 2006; Sørensen and Rubæk, 2011), while urea-based fertilization is associated with the highest GHG emissions (Chardon et al., 2007; Hu et al., 2024).

3.2.2 Environmental impact of fertilization methods in winter wheat production

The environmental impacts on winter wheat production are presented in Table 6, which shows the normalized and weighted values for the different fertilization methods. Among the fertilization methods, CPPL shows lower environmental impacts in several categories, while the impact of NPK1-NPK6 fertilizer combinations varies. The NPK fertilization methods show different environmental results under different compositions, which are analysed in detail below.

In terms of abiotic resource use (ADPe and ADPf), CPPL fertilization shows the lowest values (ADPe: 0.074, ADPf: 0.022), while for NPK fertilization methods ADPe values range from 0.105 to 0.122 and ADPf values range from 0.036 to 0.041. The NPK4 shows the highest ADPe value (0.122), indicating that its production is more resource intensive. The ADPf values show that the use of NPK5 requires the most fossil energy (0.041), while NPK2 and NPK4 (0.036) show slightly lower loads.

For the AP, only minimal differences are observed between the different fertilization methods. For CPPL fertilization the AP value is 0.250, while the NPK fertilization treatments vary between 0.234 and 0.244. This suggests that fertilization treatments alone do not result in significant differences in acidification effects.

In the EP category, CPPL fertilization has a slightly lower effect (0.181) than NPK treatments, which range from 0.178 to 0.182. NPK3 (CAN + TSP + KCl) and NPK1 (AN + TSP + KCl) show the highest eutrophication values (0.182), which may indicate that these fertilizers may be associated with higher nutrient leaching, especially due to mobilization of phosphorus and nitrogen.

In terms of GWP, the CPPL method has the lowest value (0.0449), while for NPK fertilization methods this value ranges from 0.0503 to 0.0520. NPK1 has the highest GWP value (0.0520), suggesting that the production and application of AN-based fertilizers may result in higher GHG emissions (Sylvester-Bradley et al., 2012; Rostami et al., 2015; Rahman and Forrestal, 2021).

There are no significant differences in ODP between fertilization methods. CPPL is 0.0019, while NPK fertilization treatments range between 0.0017 and 0.0019. This indicates that the type of fertilization is not a decisive factor for ozone depletion.

The CPPL for POP is 0.007, while the values for NPK treatments range from 0.009 to 0.011. The NPK1 and NPK5 fertilization treatments show the highest POP values (0.011), which may indicate that these fertilizers contribute to lower atmospheric ozone formation and the emission of oxidising substances.

For the categories of ecotoxicity potentials (FAETP, HTP, MAETP, TETP), the use of CPPL generally shows lower values. The CPPL for FAETP is 0.919, while for NPK fertilization treatments these values range from 0.944 to 0.960, suggesting that NPK fertilization increases the stress on freshwater ecosystems. In the case of HTP, the CPPL is 0.090, while the values for NPK fertilization treatments range from 0.110 to 0.123, indicating that fertilization may contribute to human health impacts. For the MAETP, the CPPL value is 0.658, while NPK treatments show higher values (between 1.060 and 1.198). NPK4 (CAN + MAP + KCl) shows the highest value (1.198), which may indicate that CAN-based fertilization has a higher impact on marine ecosystems. In the TETP, CPPL and NPK treatments have almost identical values (0.670–0.671), suggesting that soil ecotoxicity is little dependent on the fertilization method.

In conclusion, CPPL fertilization shows lower values in most environmental impact categories, in particular for GWP, EP, POP and ecotoxicity potentials (FAETP, HTP, MAETP). The use of NPK fertilization methods increases the environmental burden, in particular for NPK1, which has the highest greenhouse gas emissions, and NPK4, which has the highest ecotoxicity values. However, there is no significant difference between the different fertilization methods in the categories of ODP and AP.

According to the results, fertilization methods have a significant impact on the environmental burden of crop production (Bocianowski et al., 2016; Szulc et al., 2016; Sun et al., 2022; Mukosha et al., 2023; Zhang Y. et al., 2024). CPPL fertilization is generally more favorable, especially in terms of reducing greenhouse gas emissions (GWP) and eutrophication potential (EP). The use of chemical fertilizers, especially AN- and CAN-based fertilization, increases the depletion of abiotic resources, while urea-based fertilization contributes significantly to greenhouse gas emissions (Charles et al., 2017). Based on our results AN-based fertilization (NPK1, NPK2) increases AP, which is due to ammonia emissions. CAN-based fertilization (NPK3, NPK4) shows higher EP values, which is due to the leaching of nitrates and phosphates into groundwater, while Urea-based fertilization (NPK5, NPK6) has exceptionally high GWP values, which can be explained by the emission of nitrogen oxides. Overall, the use of CPPL can reduce the climate risks and water pollution problems of agricultural production, while the use of chemical fertilizers can in some cases achieve higher crop yields, but with a significant environmental burden.

3.3 Effect of fertilizers in feed production on environmental impact of broiler chicken production

The results of the LCA of broiler chicken production (Table 7) show that environmental impacts are significantly influenced by the way in which the plants used as feed are fertilized and whether rearing takes place in winter or summer. Maize and winter wheat with CPPL fertilization used as feed generally have a lower environmental impact, while feed crops with NPK fertilization have a higher environmental impact. In addition, the differences between winter and summer rotation are smaller, but there are detectable differences in certain impact categories.

The largest differences in environmental pressures are found in abiotic resource use. For chickens fed with CPPL-based feed, the ADPe value is 0.022 in both summer and winter, while for chickens fed with NPK-based feed, these values are much higher, ranging from 2.823 to 3.275. A similar trend can be observed for the ADPf category, where the value for CPPL is 0.045, while for NPK fertilized

TABLE 7 Normalized and weighted values for the production of 1 t broiler chicken (live weight, summer rotations) (CML-IA baseline, EU25 + 3, 2000).

Impact categories	CPPL	NPK1	NPK2	NPK3	NPK4	NPK5	NPK6
Summer							
ADPe	0.022	2.823	3.243	3.257	3.268	3.244	3.253
ADPf	0.045	1.481	1.621	1.668	1.664	1.671	1.666
AP	0.032	5.470	6.240	6.280	6.274	6.275	6.270
EP	0.117	2.892	3.292	3.403	3.400	3.402	3.400
GWP	0.364	2.159	1.982	2.340	2.339	2.346	2.346
ODP	0.002	0.072	0.084	0.085	0.085	0.085	0.085
POP	0.019	2.936	2.964	2.988	2.986	2.988	2.986
FAETP	0.378	27.346	28.252	28.612	28.618	28.601	28.604
HTP	0.106	4.769	5.290	5.389	5.395	5.381	5.386
MAETP	3.709	51.337	53.032	56.736	56.778	56.601	56.621
TETP	0.023	18.061	18.409	18.411	18.411	18.413	18.412
Total	4.817	119.346	124.409	129.169	129.218	129.007	129.029
Winter							
ADPe	0.022	2.830	3.267	3.265	3.275	3.251	3.241
ADPf	0.045	1.570	1.753	1.757	1.753	1.759	1.630
AP	0.031	5.476	6.279	6.285	6.279	6.280	6.257
EP	0.115	2.887	3.395	3.398	3.396	3.398	3.391
GWP	0.359	2.196	2.376	2.377	2.376	2.386	2.323
ODP	0.002	0.073	0.087	0.087	0.087	0.087	0.084
POP	0.018	2.949	2.999	3.002	2.999	3.002	2.977
FAETP	0.373	27.273	28.536	28.540	28.546	28.525	28.440
HTP	0.104	4.786	5.406	5.407	5.413	5.397	5.331
MAETP	3.656	50.706	56.048	56.105	56.147	55.962	54.867
TETP	0.022	18.060	18.410	18.410	18.410	18.410	18.409
Total	4.747	118.806	128.556	128.633	128.681	128.457	126.95

ADPe, Abiotic Depletion Potential of Elements; ADPf, Abiotic Depletion Potential of Fossil Fuels; AP, acidification potential; EP, eutrophication potential; ODP, ozone depletion potential; POP, photochemical oxidation potential; FAETP, freshwater aquatic ecotoxicity potential; HTP, human toxicity potential; MAETP, marine aquatic ecotoxicity potential; TETP, terrestrial ecotoxicity potential.

feeds it increases up to 1.759. This is because the production and transport of fertilized fodder crops involves significant energy use, relying in particular on fossil fuels (Manoj et al., 2022; Gaidar et al., 2024; Yadav et al., 2024).

For AP, the value for chickens fed with CPPL fertilized feed is significantly lower (0.031–0.032) than for chickens fed with chemical fertilized-based feed, where the values range from 5.470 to 6.285. This suggests that the production of NPK fertilized feed and the application of fertilizers may result in higher levels of acidifying substances such as ammonia and nitrate being released into the environment (Zhang et al., 2020; Yoon et al., 2021; Kang et al., 2022).

The EP values also show that NPK fertilization increases the environmental burden. For CPPL, the value ranges from 0.115 to 0.117, while for NPK fertilized feed it ranges from 2.887 to 3.403. The higher values suggest that the cultivation of fertilized crops may result in higher amounts of nitrogen and phosphorus being released from the soil and into water, which may lead to eutrophication.

GWP also shows significant differences between different fertilization methods. For CPPL fertilization the value is lower (0.359–0.364), while for NPK fertilization it reaches 2.346. This indicates that the cultivation of fertilized fodder crops releases higher amounts of greenhouse gases such as nitrous oxide (N_2O), which is a major contributor to climate change (Amin, 2023; Tometin et al., 2023).

ODP values show minimal differences between different fertilization methods. The value ranges from 0.002 for CPPL-based feed to 0.072 to 0.087 for NPK fertilized feed. Although the difference is relatively small, this may indicate that the emission of certain gases, such as halogenated compounds, during fertilization may contribute to ozone depletion.

The POP values for CPPL fertilized feed are lower (0.018–0.019), while for NPK fertilized feed they range from 2.936 to 3.002. This suggests that more reactive gases are produced during the cultivation and decomposition of NPK-fertilised crops, which may contribute to the formation of photochemical smog.

In terms of ecotoxicity potentials, CPPL fertilization shows lower values in all cases. For example, the MAETP value for CPPL fertilization is 3.709 in summer and 3.656 in winter, while for NPK fertilized feeds this value increases up to 56.778. This is a significant difference and suggests that the application of NPK fertilizers significantly increases the pressure on marine ecosystems, probably due to nutrient leaching (Bender and Heijden, 2014; Howley et al., 2018).

The differences between winter and summer rotation are smaller, but differences are observed in some impact categories. AP, EP and GWP values are slightly higher in winter than in summer, which may indicate that the energy demand of animals is higher in winter, for example, due to heating needs (Hotta et al., 2007; David et al., 2014). However, the differences are not significant, indicating that seasonal variation has less impact on environmental pressures than the way in which the crops used as feed are fertilised.

In the context of broiler chicken production systems, the results show that feeding fodder crops with CPPL fertilization has more beneficial environmental effects, especially in terms of abiotic resource use, AP, EP, GWP and ecotoxicity potentials (FAETP, HTP, MAETP, TETP). In contrast, growing crops with NPK fertilizers has a higher environmental impact, mainly due to the fertilization processes and the emissions they cause. The differences between winter and summer crop rotations are smaller but can be seen in some cases, especially because of seasonal changes in the energy needs of livestock.

The environmental impacts of broiler chicken farming also depend significantly on the fertilization methods used in feed production. According to the LCA results, chickens fed with crops grown with CPPL fertilization had a lower environmental impact. In terms of AP and EP, CPPL-based feeding reduced the effects of acidification and eutrophication, as less nitrate and phosphate were released into the environment. In addition, the use of CPPL reduced greenhouse gas emissions from broiler chicken farming, particularly N_2O and CO_2 emissions.

In the case of feed crops grown with fertilizers, CAN- and urea-based fertilization in particular showed a higher impact on marine and freshwater ecosystems, which is in line with other studies (Zhang et al., 2020).

A comparison of winter and summer broiler chicken production showed that, although the differences are not significant, the environmental impact is slightly higher in winter, especially in terms of AP and EP (manure emissions and the resulting nitrate and phosphate loads are higher in winter) and in the case of GWP (energy consumption is higher during winter due to heating requirements, which increases CO_2 emissions). However, the differences are not drastic, and other studies have shown that the differences in seasonal effects can be explained more by energy consumption and ammonia emissions than by feed type (Pelletier et al., 2008).

4 Conclusion

Based on the results of the research, it can be concluded that the use of composted and pelletized poultry litter (CPPL) offers significant environmental benefits over traditional chemical fertilizers in several areas of agriculture. Life cycle assessment (LCA) showed that the use of CPPL can reduce greenhouse gas emissions (GWP), the depletion of mineral resources (ADPe and ADPf), and the ecological pressure on freshwater and marine ecosystems (FAETP and MAETP). However, the use of CPPL was associated with increased acidification (AP) and eutrophication potential (EP), mainly due to ammonia emissions and the leaching of organic nutrients from the soil.

In the crop production sector, particularly for maize and winter wheat, CPPL-based nutrient replenishment showed more favorable values in most environmental impact categories compared to various NPK fertilizer combinations. The results show that different types of fertilizers (AN, CAN, urea, etc.) contribute to environmental pressure to varying degrees: while AN- and CAN-based fertilizers significantly increase AP and EP values, urea-based fertilizers are mainly unfavorable in terms of greenhouse gas emissions.

In the broiler chicken production sector, the method of fertilizing feed crops had a decisive influence on the environmental impact of production. In the case of animals fed with feed crops fertilized with CPPL, we observed lower loads in almost all environmental categories examined, especially in GWP, AP, EP, and ecotoxicity indicators. Seasonal differences were moderate: slightly higher environmental impacts were observed in the winter cycle, mainly due to energy consumption for heating.

The relevance of the study is reinforced by the fact that the European Union's Green Deal and Farm to Fork strategy prioritize the reduction of synthetic inputs (e.g., fertilizers) and the promotion of circular farming. The results of the research directly support the achievement of the Sustainable Development Goals (SDG 12 – Responsible consumption and production; SDG 13 – Climate action).

Future research should include a detailed economic analysis of the applicability of CPPL technologies, with a particular focus on costs, crop yields and return on investment. Another important task is technological optimization, especially to reduce ammonia losses and nutrient leaching, which requires improvements in application timing and techniques. The modeling results of this research need to be validated in the field through longer-term field trials in different agroecological regions. Finally, environmental policy integration is of paramount importance: based on the results, it would be justified to encourage CPPL-based fertilization in national and EU agricultural support schemes, in line with the objectives of sustainable agriculture.

Overall, CPPL offers an environmentally friendly alternative to chemical fertilizers and can play an important role in the development of sustainable, circular agricultural systems. With appropriate application strategies, it can contribute to climate change mitigation, water quality protection and reduced pressure on ecosystems.

Based on the results, the initial objectives of the study were successfully achieved, confirming that CPPL can be a viable and environmentally beneficial alternative in both crop and broiler production systems.

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

NÉK: Visualization, Validation, Methodology, Data curation, Conceptualization, Writing – original draft, Software, Investigation, Formal Analysis. AN: Supervision, Writing – review and editing, Conceptualization, Methodology, Resources. JT: Funding acquisition, Resources, Writing – review and editing, Supervision.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The research presented in the article was carried out within the framework of the Széchenyi Plan Plus program with the support of the RRF 2.3.1 21 2022 00008 project. Supported by the EKÖP-24-4 University Research Scholarship Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund.

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.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. The author(s) verify and take full responsibility for the use of generative AI in the preparation of this manuscript. Generative AI (ChatGPT by OpenAI) was used under author supervision to support language editing and stylistic improvement. All content, interpretations, and conclusions were critically reviewed and approved by the authors.

Publisher's note

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