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RESEARCH ARTICLE

Livestock waste management for energy recovery in Brazil: a life cycle assessment approach

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Abstract

Livestock farming has exerted intense environmental pressure on our planet. The high emissions to the environment and the high demands of resources for the production process have encouraged the search for decarbonization and circularity in the livestock sector. In this context, the objective of this study was to evaluate and compare the environmental performance of two different uses for biogas generated in the anaerobic digestion of animal waste, either for electricity generation or biomethane. For this purpose, a life cycle assessment approach was applied to evaluate the potential of anaerobic digestion as a management technology for three different livestock wastes, related to beef cattle, dairy, and sheep in the Brazilian animal production context. The results suggest that the treatment scenarios focusing on biomethane generation were able to mitigate the highest percentage of damages (77 to 108%) in the global warming category when compared to the scenarios without the use of anaerobic digestion ($3.00 \cdot 10^2$ to $3.71 \cdot 10^3$ $kgCO_{2\,eq}$) or in the perspective of electricity generation (mitigation of 74 to 96%). In terms of freshwater eutrophication, the generation of electricity ($-2.17 \cdot 10^{-2}$ to $2.31 \cdot 10^{-3}$ kg P_{eq}) is more favorable than the purification of biogas to biomethane ($-1.73 \cdot 10^{-2}$ to $2.44 \cdot 10^{-3}$ kg P_{eq}), due to the loss of methane in the upgrading process. In terms of terrestrial ecotoxicity, all scenarios are very similar, with negative values ($-1.19 \cdot 10^1$ to $-7.17 \cdot 10^2$ kg 1,4-DCB) due to the benefit of nutrient recovery, especially nitrogen, associated with the use of digestate as fertilizer, which was one of the critical points in all scenarios. Based on these results, it is evident that proper management of all stages of the treatment life cycle is the key to decarbonization and circularity in livestock waste management. The biogas use does not present different effects on the environmental performance of the scenarios studied, demonstrating that the purpose should be chosen according to the needs of each plant or management system.

Keywords Biogas · Anaerobic digestion · Circular economy · Manure · Waste to energy · Biomethane

Abbreviations

BS1	Baseline scenarios 1
BS2	Baseline scenarios 2
BS3	Baseline scenarios 3
CLB	Covered lagoon biodigester
FU	Functional unit
GHG	Greenhouse gases
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NMHC	Non-methane hydrocarbons
PM	Particulate matter

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Introduction

Several management strategies aimed at the development and improvement of energy recovery technologies through renewable sources have gained prominence in recent years (Awasthi et al. 2022). The need to reverse the climate change scenario due to global warming has been the basis of the discussion for the adoption of a circular economy worldwide (Styles et al. 2022). According to the Ellen MacArthur Foundation (2021), it is necessary to change the current linear model of "take-make-waste" to an economy that is regenerative by design; that is, it is necessary to design systems in such a way that waste is avoided and recovery and reuse are improved. By reducing the extraction of natural resources and the associated emissions, the carbon footprint of production and consumption is reduced (Bellezoni et al. 2022).

Thus, the search for the decarbonization of productive sectors has been betting on circular management as a key strategy for the achievement of mitigation goals for greenhouse gases (GHGs). With this, anaerobic digestion has played an important role in the management of waste from a circular perspective, actively contributing to the reduction of greenhouse gas emissions, as well as the dependence on fossil fuels, one of the biggest global challenges today (Shinde et al. 2021; Mehta et al. 2022).

Anaerobic digestion is a biological process capable of converting biodegradable substrates into an energy-rich gas with multiple uses, ranging from heat and electricity generation to vehicle fuel (Adghim et al. 2020; Sinigaglia et al. 2022). In addition, the process of anaerobic digestion enables the use of nutrients present in the waste, such as nitrogen, phosphorus, and potassium, which end up being important biofertilizers in terms of global food security (Walling and Vaneeckhaute 2020). Among the organic waste used as substrate in the process of anaerobic digestion, animal waste stands out. In Brazil, about 80% of existing plants operate with the digestion of this type of waste (CIBiogas 2021).

The livestock sector is one of the largest emitters of pollutant gases worldwide; according to FAO (2020), in 2018, annual GHG emissions from livestock manure were more than 1.4 Bt of $CO_{2\ eq}$, methane being one of the main contributors to the activity. Methane is one of the main GHGs, and Brazil is the fifth largest emitter of methane in the world; according to data from SEEG (System of Estimates of Emissions and Removals of Greenhouse Gases), the agricultural sector is responsible for the largest emission of this methane, equivalent to 14.54 Mt in 2020, which represents 71.8% of the total emitted in the country, and 5.8% (0.85 Mt CH_4) is due to the management of animal waste (Potenza et al. 2021). The climate observatory also points out that if emission mitigation measures are not taken until 2030, at the current pace of agricultural and livestock production, emissions will increase by 5.6%, going against the commitment made at COP26, held in 2021 in Glasgow, Scotland, in which Brazil committed to contribute to reducing global methane emissions by 30% by 2030, in relation to 2020 levels (Alencar et al. 2021; Arora and Mishra 2021).

With a production that expands every year, the management of the waste generated, from a perspective of energy use, is essential for the sustainability of the production chain, given the contribution that the sector presents in terms of emissions (Cheng et al. 2020). Thus, the incentive for the adoption of anaerobic digestion technology through public policies around the world is driving the progressive development of technologies aimed at waste management in a circular context (Sagastume Gutiérrez et al. 2022).

Brazil has fostered the adoption of technologies aimed at decarbonization, with the use of renewable fuels and the establishment of public policies focused on the topic. In 2020, the National Policy for Biofuels (RenovaBio) came into force, which aims to increase the participation of biofuels in order to reduce GHG emissions in the country (Brasil 2017; Sinigaglia et al. 2022); in the agricultural sector, the Low-Carbon Agriculture Plan (ABC) (Brasil 2021) has encouraged the adoption of anaerobic digestion treatment for animal waste as a mechanism for mitigating emissions of pollutants from the sector, while the incentive for Renewable Sources of Electric Energy (PROINFA) (Brasil 2002) aims to diversify the Brazilian energy matrix, with biomass as an important energy contributor (Sinigaglia et al. 2022).

Despite the incentive to adopt measures to mitigate emissions and reduce the use of fossil fuels, the viability of the processes, in environmental terms, must be carefully evaluated to ensure the benefits of the management adopted (Awasthi et al. 2022). Thus, understanding the magnitude of the impacts, as well as the main weak points, is fundamental to the direction of strategies for improvement (Ioannou-Ttofa et al. 2021). In this sense, life cycle studies help to identify and compare critical points of the technological choices adopted for waste management.

Of the existing papers, some have focused on evaluating and comparing the implications of the use of the biogas generated in anaerobic digestion, comparing the impacts related to electricity generation or use as vehicular fuel. Valli et al. (2017) estimated the life cycle GHG emissions of electricity and biomethane produced by four Italian biogas plants, which operate with various wastes, including agricultural. Masilela and Pradhan (2021), meanwhile, used life cycle assessment (LCA) to compare the multiple uses of biomethane generated from organic waste streams in an African context. Tian et al. (2021) compared the environmental sustainability of different applications of biogas for electricity generation, cooking fuel, and transportation fuel for centralized and decentralized Singapore plants. Alengebawy et al. (2022) applied the LCA of biogas fuel use, considering heat and power generation, burning in steam boilers, and upgrading for fuel generation, to determine the most sustainable option. Poeschl et al. (2012) conducted an LCA of biogas production and use from different wastes, focusing on energy crops and the multiple uses for biogas. Natividad

Pérez-Camacho et al. (2019), in turn, conducted a life cycle analysis of an anaerobic digestion plant in Northern Ireland, with feedstock from cattle manure and grass silage, to compare the environmental impacts of biogas production and use as a substitute for grid electricity, natural gas grid, and transport fuels. At the same time, Shinde et al. (2021) evaluated and compared the environmental impact of the production and use of biomethane for electricity and vehicular fuel for public transport buses in Västerås, Sweden. Di Maria et al. (2016) considered three different uses of biomethane from municipal organic waste digestion—injection into the natural gas grid, use for cogeneration, and use as vehicle fuel—and evaluated the LCA of these energy uses from an Italian perspective. Moghaddam et al. (2016), in turn, evaluated the use of biogas from the anaerobic digestion of corn as a fuel or for combined heat and power generation. Tilche and Galatola (2008) studied the contribution of anaerobic digestion of waste to the reduction of GHG emissions for 27 EU countries, analyzing two possible applications of biogas: electricity production from manure waste and production of methane for vehicles from biogas from landfills and sludge from municipal and industrial wastewater treatment. Ardolino et al. (2018) studied the environmental sustainability of biomethane production by anaerobic digestion of the separately collected organic fraction of municipal solid waste, as well as the implications of the end use given to the biogas.

Although these studies have focused on LCA to evaluate the impacts of anaerobic digestion of waste from an energy perspective, different objectives, assumptions, and system boundaries, as well as varying sources of inputs and energy, plant location, and level of technological development, make it difficult to compare and extrapolate the results, which makes life cycle studies targeted to the specific study objective (Esteves et al. 2019; Tian et al. 2021). Furthermore, none of these studies were specific to the treatment of animal waste from the beef, dairy, and sheep meat production chains in a Brazilian production context, given the significance of the Brazilian livestock sector, with a production of 8.4 Mt of beef and 35.4 Bl of milk in the year 2022 (Brasil 2022) and a herd of 20.5 million sheep, in the year 2021 (IBGE 2021). The environmental sustainability of the treatment of the waste generated is of utmost importance to help mitigate GHG emissions and meet established environmental targets since the projection is that national production will expand in the coming years; by 2032, the production should increase by 14.9% for beef and 19.8% for milk (Brasil 2022).

With this, this paper proposes to address these research gaps by evaluating, comparing, and understanding the magnitude of the impacts of livestock waste management through a life cycle study of the anaerobic digestion of this waste, comparing different uses of biogas for electricity generation or biomethane for vehicular fuel. Thus, the results of this study can assist in the development of operation models of treatment plants, as well as public policymakers regarding the environmental sustainability of the use of anaerobic digestion for the treatment of livestock waste and the multiple uses of biogas in favor of circularity of the productive system.

Methods

Life cycle assessment: goal and scope

A life cycle study was conducted to evaluate and compare the environmental performance of two strategies for the energy use of biogas generated from animal waste from different livestock activities in Brazil, i.e., for the generation of electricity (case A) or the generation of vehicular biomethane (case B).

The LCA was conducted following the ISO 14040 (2006) and ISO 14044 (2006), considering an expanded frontier attributional approach, in which the products generated are used as substitutes for commercial products, avoiding their production and consequent environmental damage.

Description of scenarios and system boundaries

Three operating treatment plants that benefit from the waste generated to obtain energy through the anaerobic digestion of animal waste were evaluated. The scope of the system includes manure storage for stabilization of organic matter and subsequent uses in the field and/or production of biogas for electricity generation or biomethane, followed by storage of the digestate and/or composting, with subsequent use in the field as fertilizer (Fig. 1).

For the evaluation of environmental impacts, the treatment of 1 t of manure was considered a functional unit (FU). Impacts associated with the construction and decommissioning phases of physical facilities were not considered since studies showed that impacts during the operation phase were the most significant (Esteves et al. 2019).

The units under study present different livestock activities; scenario 1 (Fig. 1(b)) comprises a plant located in the state of Minas Gerais-Brazil whose activity is beef cattle farming; in a feedlot system, the waste of about 6.6 thousand animals is digested in covered lagoon biodigester (CLB), the biogas generated is converted into electricity, and the digestate is used as biofertilizer (Table 1.A in supplementary material).

Scenario 2 (Fig. 1(d)), on the other hand, comprises the plant located in the state of Paraná-Brazil, whose production is focused on dairy cattle farming in a free stall confinement system. In this scenario, the daily milk production is around 32 Kl, and the waste is scraped from the

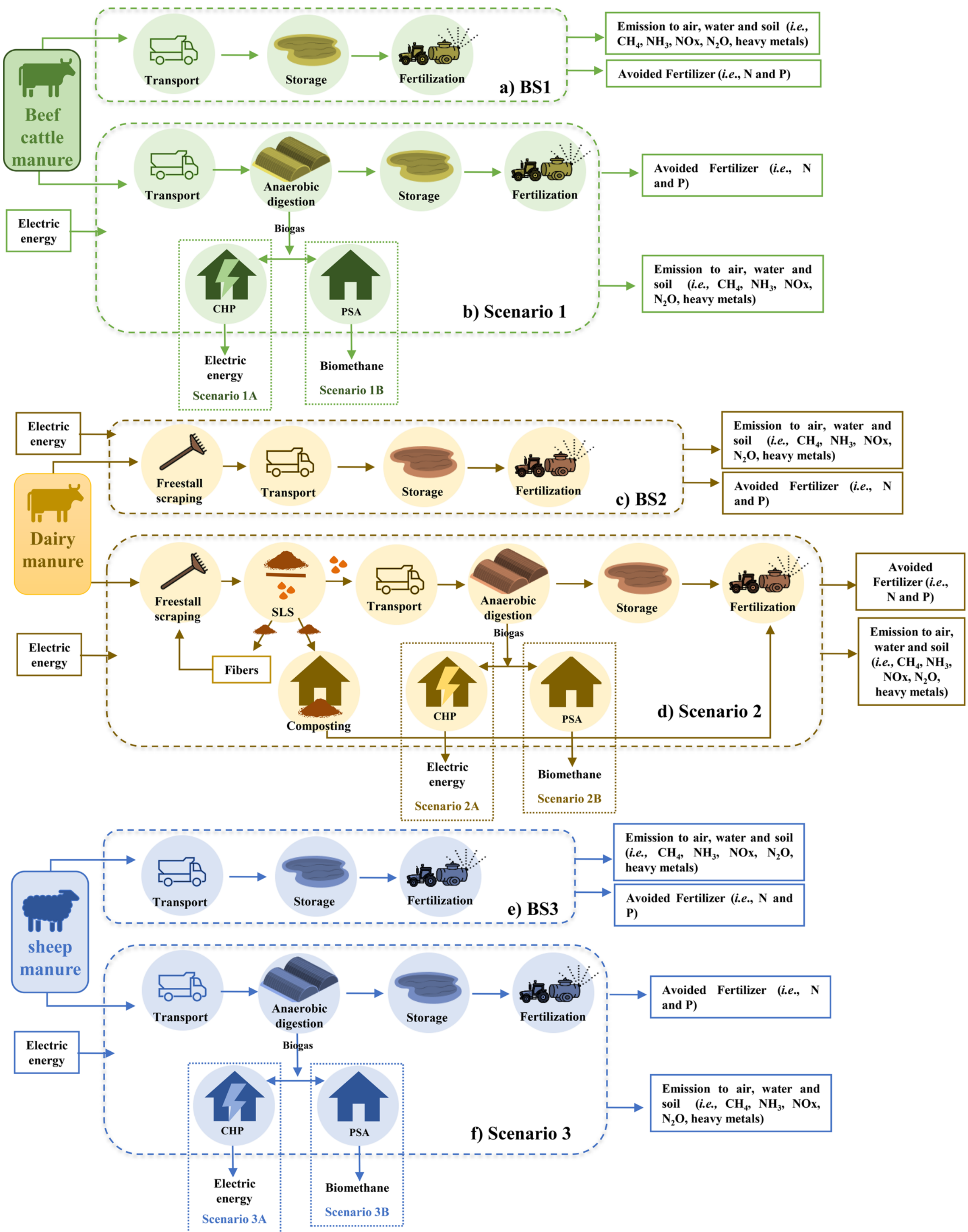

Fig. 1 Schematic representation of all scenarios. System boundaries are represented by the dotted box, where the arrows indicate the direction of flows for the two biogas end use cases (electric energy and biomethane). CHP, combined heat and power cogeneration; PSA, pressure swing adsorption

facilities and separated mechanically into a solid fraction (15% v v^{-1}), which is directed to composting 80% and for bedding 20%. The liquid fraction (85%) is sent to the CLB, along with the biogas used to generate electric electricity and the digestate as a biofertilizer.

The other treatment plant located in the state of Minas Gerais-Brazil has sheep farming as its main activity and was defined as scenario 3 (Fig. 1(f)). This plant is responsible for treating the waste of about 27,000 heads of sheep raised in confinement. As in the other scenarios, the waste is managed in CLB, and the biogas is used to generate electricity and digestate as biofertilizer.

To compare whether the management of waste through anaerobic digestion presented improvements in the environmental performance of the productive units, for each waste, baseline scenarios were stipulated, considering the management of waste in deep pits with subsequent application to the soil, being BS1 (Fig. 1(a)) for the waste from beef cattle, BS2 (Fig. 1(c)) for the waste from dairy cattle, and BS3 (Fig. 1(e)) for sheep.

Life cycle inventory

For the construction of the life cycle inventory (LCI), all inputs and outputs related to the system boundaries were considered. The inventory used primary data from the plant (Table 1.A in supplementary material) and, when absent, was estimated based on relevant literature, in addition to data from the Ecoinvent (2021).

The CH_4 emissions from storage were estimated by the model presented by Sardá et al. (2018) considering the storage time of 120 days for the baseline scenarios (BS1, BS2, and BS3) and 60 days for the other scenarios, as well as the volatile solid content present in the raw manure of 42% for BS1, 5.26% for BS2, and 56% for BS3 and the volatile solids of the digestate presented in Table 1.A (in supplementary material) for the other scenarios. The NH_3 loss was estimated according to the model presented by Kunz and Mukhtar (2016), which considers the chemical balance of ammonia between the gas and liquid fraction in terms of free ammonia, and the total ammoniacal nitrogen content was 3023 mgN L^{-1} for BS1, 588.32 mgN L^{-1} for BS2, and 1612 mgN L^{-1} for BS3 and for the other scenarios according to values present in the digestate (Table 1.A in supplementary material).

For fertilization, the use of an agricultural tractor for transportation and sprinkler application was considered from the Ecoinvent (2021) database inventory, with a rate of 80 m^3 ha^{-1}, calculated according to the nutrient demand for a corn crop (da Silva et al. 2016). Emissions from the agricultural application, considered in all scenarios, were estimated according to emission factors presented by Cherubini et al. (2015) using the nitrogen, ammonia, zinc, copper, and phosphorus concentration of the manure and digestate (Table 2.A in supplementary material). The estimates presented by Cherubini et al. (2015) were also used to determine the emissions related to composting and the application of the solid compost present in scenario 2.

The avoided impacts of phosphate and nitrogen fertilizers were also considered in all scenarios, using inventories from the Ecoinvent (2021) database, estimated based on the nitrogen and phosphorus content of the digestate, in addition to the avoided electric energy or fuel.

Life cycle inventory for the baseline scenarios

In the inventory of the baseline scenarios (Table 1), internal transport by truck from the Ecoinvent (2021) database and storage of animal waste in deep pits for about 120 days, with subsequent application to the soil as biofertilizer, were considered.

Life cycle inventory for the prospect of electricity generation

In the inventory of biogas use for electric power generation (Table 2), the use of electric power for the Brazilian region in which the project is located (southeast or south), the manure transport to the biodigester, and the generation of electric power in the motor generator were considered, according to data from Ecoinvent (2021). In addition, the avoided impacts from electricity generation (using factors from the regional electricity matrix) and fertilizer substitution were considered, according to the Ecoinvent (2021). The emissions from the different stages were estimated as already discussed.

Life cycle inventory for biomethane generation perspective

In the inventory of biogas use for biomethane generation (Table 3), the use of electricity was considered for the Brazilian region in which the project is located (southeast or south), the transport of waste to the biodigester and the biogas upgrading process, considering the PSA process (adsorption by pressure oscillation) as presented by Jungbluth et al. (2007) and available in the Ecoinvent (2021) database. In addition, the avoided impacts of diesel use were considered using the emission factors presented in the 1st National Inventory of Atmospheric Emissions by Motor Vehicles (MMA 2011) and the avoided diesel production, adapted from the Ecoinvent (2021) database, including the biodiesel content of Brazilian diesel (12%). In addition, the benefits of avoided fertilizer use were accounted for in all scenarios.

Life cycle impact assessment (LCIA)

The evaluation was performed using SimaPro software, and the evaluation methodology was ReCiPe Midpoint (H) 2016

Table 1 Inventory for the baseline scenarios (FU = 1 t of manure)

		BS1 (beef cattle)	BS2 (dairy)	BS3 (sheep)
Input				
Reference flow	Manure (tonne)	1.00	1.00	1.00
Soil application process	Fertilizing, by broadcaster (ha)	$1.25\cdot10^{-2}$	$1.25\cdot10^{-2}$	$1.25\cdot10^{-2}$
Internal transport	Transport; freight, lorry 3.5–7.5 metric ton (tkm)	1.00	4.00	2.50
Use of electrical energy	Electricity; medium voltage {BR-southern or south grid} (kWh)	n.a	2.16	n.a
Outputs				
Fertilizers avoided	Nitrogen fertilizer; as N (kg)	$1.60\cdot10^{2}$	1.59	$1.55\cdot10^{2}$
	Phosphate fertilizer, as P_2O_5 (kg)	2.13	$7.00\cdot10^{-1}$	$1.04\cdot10^{1}$
Emissions to air from storage	Methane, biogenic (kg $_{CH4}$)	$8.70\cdot10^{1}$	8.87	$1.16\cdot10^{2}$
	Ammonia (kg $_{NH3}$)	$2.50\cdot10^{-1}$	$1.23\cdot10^{-1}$	$1.60\cdot10^{-1}$
Emissions to air from soil application	Ammonia (kg $_{NH3}$)	1.13	$6.10\cdot10^{-1}$	$7.70\cdot10^{-1}$
	Dinitrogen monoxide (kg $_{N2O}$)	2.19	$2.20\cdot10^{-2}$	2.12
	Nitrogen monoxide (kg $_{NO}$)	$4.40\cdot10^{-1}$	$2.40\cdot10^{-1}$	$3.00\cdot10^{-1}$
Emissions to water from soil application	Nitrate (kg $_{NO3}$)	$6.31\cdot10^{1}$	$6.30\cdot10^{-1}$	$6.10\cdot10^{1}$
	Phosphorus (kg $_{P}$)	$4.40\cdot10^{-3}$	$3.20\cdot10^{-3}$	$9.00\cdot10^{-3}$
Emissions to the soil from soil application	Zinc[a] (kg)	$6.00\cdot10^{-1}$	$2.98\cdot10^{-3}$	$1.00\cdot10^{-3}$
	Copper[a] (kg)	1.10	$2.28\cdot10^{-3}$	$2.30\cdot10^{-4}$

n.a not applicable

[b]Estimated as presented by Junqueira (2011), where Zn is equal to 0.06% of the raw manure and Cu is 0.11%

(Huijbregts et al. 2017). According to Zira et al. (2021), the environmental impacts of livestock activities are related to emissions to soil, water, and/or air, as well as in function of the demand for resources; in this sense, considering the emerging issues related to livestock, the following impact categories were evaluated: global warming; stratospheric ozone depletion; ozone formation-terrestrial ecosystem; freshwater eutrophication; terrestrial ecotoxicity; and terrestrial acidification. For the interpretation of the results, we followed the recommendations presented by Zampori et al. (2016) in the "Guide for interpretation of life cycle assessment results," which defines the significant aspects to be considered when assessing the results.

Sensitivity and uncertainty analysis

A sensitivity analysis was performed by varying the percentages of emissions from the digestate application step to the soil to verify how an increase or decrease in emissions would affect the overall performance of each scenario, simulating the effects of adopting different digestate application technologies (such as spraying and incorporation, for example). Finzi et al. (2019) reported that the incorporation of digestate, in comparison to sprinkling, can promote a reduction of up to 60% in gas emissions, such as ammonia; due to this, a variation of 40% and 60% in emissions was considered in this step (Hollas et al. 2023).

To assess the uncertainty associated with the accuracy of the data, a pedigree matrix was implemented using the Ecoinvent data quality system from the SimaPro software (Ciroth et al. 2016). A Monte Carlo simulation was then run with 1000 iterations to accurately measure the level of uncertainty in our findings, with a 95% confidence interval. Finally, to determine the statistical significance of the difference in the common averages resulting from the common uncertainties, the modified null hypothesis significance test (NHST) was used, as described by Mendoza Beltran et al. (2018), with a *p*-value of 5%.

Results and discussion

Environmental performance of livestock waste management scenarios from the perspective of electricity generation

The results of the environmental impact assessment from the perspective of electricity generation (Table 3.A in supplementary material) show that, in general, the management of livestock waste through anaerobic digestion promotes significant improvements in the environmental performance of the production units in practically all the impact categories analyzed (Table 7.A in supplementary material).

For the global warming category, for all the reference scenarios (BS1, BS2, and BS3), the stage that contributed

Table 2 Inventory for the perspective of electricity generation (FU = 1 t of manure)

		Scenario 1A	Scenario 2A	Scenario 3A
Input				
Reference flow	Manure (tonne)	1.00	1.00	1.00
Electricity	Electricity, medium voltage {BR-southern or south grid} (kWh)	$1.20 \cdot 10^1$	4.25	$2.10 \cdot 10^1$
Generator	Heat and power cogeneration, biogas, gas engine (kWh)	$2.16 \cdot 10^2$	8.58	$3.95 \cdot 10^2$
Internal transport	Transport, freight, lorry 3.5–7.5 metric ton, EURO3 (tkm)	1.00	1.26	2.50
Outputs				
Fertilizer avoided	Nitrogen fertilizer, as N (kg)	$1.49 \cdot 10^2$	1.52	$1.44 \cdot 10^2$
	phosphate fertilizer, as P_2O_5 (kg)	1.67	$4.30 \cdot 10^{-1}$	8.14
Electrical energy avoided	Electricity, medium voltage {BR-southern or south grid} (kWh)	$2.16 \cdot 10^2$	8.58	$3.95 \cdot 10^2$
Emissions to air from pond storage	Methane, biogenic (kg $_{CH4}$)	$1.15 \cdot 10^1$	2.30	$1.25 \cdot 10^1$
	Ammonia (kg $_{NH3}$)	$5.69 \cdot 10^{-2}$	$8.00 \cdot 10^{-2}$	$3.30 \cdot 10^{-2}$
Emissions to air from soil application of liquid digestate	Ammonia (kg $_{NH3}$)	1.18	$6.10 \cdot 10^{-1}$	$7.10 \cdot 10^{-1}$
	Dinitrogen monoxide (kg $_{N2O}$)	1.16	$1.10 \cdot 10^{-2}$	1.13
	Nitrogen monoxide (kg $_{NO}$)	$4.60 \cdot 10^{-1}$	$2.40 \cdot 10^{-1}$	$2.80 \cdot 10^{-1}$
Emissions to water from soil application (liquid digestate)	Nitrate (kg $_{NO3}$)	$5.50 \cdot 10^1$	$5.38 \cdot 10^{-1}$	$5.33 \cdot 10^1$
	Phosphorus (kg $_{P}$)	$4.00 \cdot 10^{-3}$	$2.72 \cdot 10^{-3}$	$8.00 \cdot 10^{-3}$
Emissions to the soil from soil application of liquid digestate	Zinc (kg)	$5.04 \cdot 10^{-1}$	$2.50 \cdot 10^{-3}$	$9.00 \cdot 10^{-4}$
	Copper (kg)	$9.13 \cdot 10^{-1}$	$1.89 \cdot 10^{-3}$	$1.88 \cdot 10^{-4}$
Emissions to air from soil application of solid biofertilizer	Ammonia (kg $_{NH3}$)	n.a	$8.00 \cdot 10^{-4}$	n.a
	Dinitrogen monoxide (kg $_{N2O}$)	n.a	$5.12 \cdot 10^{-4}$	n.a
	Nitrogen (kg $_{N2}$)	n.a	$2.30 \cdot 10^{-3}$	n.a
	Nitrogen monoxide (kg $_{NO}$)	n.a	$3.28 \cdot 10^{-4}$	n.a
Emissions to water from soil application of solid biofertilizer	Nitrate (kg $_{NO3}$)	n.a	$2.42 \cdot 10^{-2}$	n.a
	Phosphorus (kg $_{P}$)	n.a	$4.61 \cdot 10^{-4}$	n.a
Emissions to air from compost	Ammonia (kg $_{NH3}$)	n.a	$8.50 \cdot 10^{-3}$	n.a
	Dinitrogen monoxide (kg $_{N2O}$)	n.a	$1.00 \cdot 10^{-2}$	n.a
	Nitrogen monoxide (kg $_{NO}$)	n.a	$2.60 \cdot 10^{-4}$	n.a
	Methane, biogenic (kg $_{CH4}$)	n.a	$5.10 \cdot 10^{-2}$	n.a

n.a not applicable

most to the impacts generated is the storage lagoon, which corresponded to 66% of the emissions for BS1, 94% for BS2, and 73% for BS3 (Fig. 2(a), (d), and (g), respectively), emitting up to 3942.13 kg $CO_{2\ eq}$ t_{manure}^{-1} stored in BS3. In the scenarios focusing on energy use, the digested manure storage lagoon also presents a significant contribution to greenhouse gas emissions, emitting 627.82 kg$CO_{2\ eq}$ in scenario 1A (Fig. 2(b)), 78.13 kg $CO_{2\ eq}$ in scenario 2A (Fig. 2(e)), and 880.13 kg$CO_{2\ eq}$ in scenario 3A (Fig. 2(h)).

In addition to the gases emitted in the storage stages, the digestate soil application as fertilizer also contributes significantly to the impacts in the global warming category of scenarios 1A (27%), 2A (4%), and 3A (16%), by the emission of N_2O in the application process. Scenario 2A for the composting step is a potential GHG emitter (4.77 kg $CO_{2\ eq}$). Although the emissions of these phases impact the environmental performance of the scenarios, the recovery of nutrients and consequently avoiding the use of commercial fertilizers produce important benefits in all scenarios evaluated, even mitigating up to 40% of the impacts (scenario 1A).

This is because the production of fertilizers, especially nitrogenous fertilizers, uses a large amount of energy, representing up to 1% of the world's energy use, with a high dependence on fossil sources (Norskov and Chen 2016). Thus, they end up having high emission factors; according to Walling and Vaneeckhaute (2020), the production of urea is responsible for the emission of 1.3 to 4 kg $CO_{2\ eq}$ per kg of N produced, while triple superphosphate has an emission factor ranging from 0.4 to 1.6 kg $CO_{2\ eq}$ per kg of P_2O_5 produced and potassium chloride from 0.14 to 0.25

Table 3 Inventory for the perspective of biomethane generation (FU = 1 t of manure)

		Scenario 1B	Scenario 2B	Scenario 3B
Input				
Reference flow	Manure (tonne)	1.00	1.00	1.00
Internal transport	Transport, freight, lorry 3.5–7.5 metric ton, EURO3 (tkm)	1.00	1.26	2.50
Electricity	Electricity, medium voltage {BR-southern or south grid} (kWh)	$1.20·10^1$	4.25	$2.10·10^1$
Purification of biomethane from biogas	Methane, 96% by volume, from biogas, low pressure, at user (MJ)	$3.19·10^3$	$1.69·10^2$	$5.69·10^5$
Outputs				
Avoided diesel production	Diesel {BR}|soy biodiesel, production, at plant (kg)	$7.54·10^1$	4.00	$1.35·10^2$
Fertilizer avoided	Nitrogen fertilizer, as N (kg)	$1.49·10^2$	1.52	$1.44·10^2$
	Phosphate fertilizer, as P_2O_5 (kg)	1.67	$4.30·10^1$	8.14
Biomethane	Passenger car, methane 96% vol., from biogas (m^3)	$9.32·10^1$	4.95	$1.66·10^2$
Emissions to air from pond storage	Methane, biogenic (kg $_{CH4}$)	$1.15·10^1$	2.30	$1.25·10^1$
	Ammonia (kg $_{NH3}$)	$5.69·10^{-2}$	$8.00·10^{-2}$	$3.40·10^{-2}$
Emissions to air from soil application of liquid digestate	Ammonia (kg $_{NH3}$)	1.18	$6.10·10^{-1}$	$7.10·10^{-1}$
	Dinitrogen monoxide (kg $_{N2O}$)	1.16	$1.10·10^{-2}$	1.13
	Nitrogen monoxide (kg $_{NO}$)	$4.60·10^{-1}$	$2.40·10^{-1}$	$2.80·10^{-1}$
Emissions to water from soil application (liquid digestate)	Nitrate (kg $_{NO3}$)	$5.50·10^1$	$5.38·10^{-1}$	$5.33·10^1$
	Phosphorus (kg $_{P}$)	$4.00·10^{-3}$	$2.72·10^{-3}$	$8.00·10^{-3}$
Emissions to the soil from soil application of liquid digestate	Zinc (kg)	$5.04·10^{-1}$	$2.50·10^{-3}$	$9.00·10^{-4}$
	Copper (kg)	$9.13·10^{-1}$	$1.89·10^{-3}$	$1.88·10^{-4}$
Emissions to air from soil application of solid biofertilizer	Ammonia (kg $_{NH3}$)	n.a	$8.00·10^{-4}$	n.a
	Dinitrogen monoxide (kg $_{N2O}$)	n.a	$5.12·10^{-4}$	n.a
	Nitrogen (kg $_{N2}$)	n.a	$2.30·10^{-3}$	n.a
	Nitrogen monoxide (kg $_{NO}$)	n.a	$3.28·10^{-4}$	n.a
Emissions to water from soil application of solid biofertilizer	Nitrate (kg $_{NO3}$)	n.a	$2.42·10^{-2}$	n.a
	Phosphorus (kg $_{P}$)	n.a	$4.61·10^{-4}$	n.a
Emissions to air from compost	Ammonia (kg $_{NH3}$)	n.a	$8.50·10^{-3}$	n.a
	Dinitrogen monoxide (kg $_{N2O}$)	n.a	$1.00·10^{-2}$	n.a
	Nitrogen monoxide (kg $_{NO}$)	n.a	$2.60·10^{-4}$	n.a
	Methane, biogenic (kg $_{CH4}$)	n.a	$5.10·10^{-2}$	n.a
Diesel burning avoided	CO_2 (kg)	$2.01·10^2$	$1.27·10^1$	$3.60·10^2$
	CO (g)	$3.55·10^2$	$1.58·10^1$	$6.33·10^2$
	NMHC (g)	$6.83·10^1$	3.04	$1.22·10^2$
	NOx (g)	$7.70·10^2$	$3.43·10^1$	$1.37·10^3$
	PM (g)	7.72	$3.40·10^{-1}$	$1.38·10^1$

n.a not applicable; *PM* particulate matter, *NMHC* non-methane hydrocarbons

kg $CO_{2\,eq}$ per kg of K_2O produced; thus, nutrient recovery is important in terms of minimizing GHG emissions.

Besides the benefits of the recovery of fertilizers, it is evident the contribution that energy use promotes in terms of greenhouse gas emissions; the gases that before would be emitted into the atmosphere, mainly in the form of methane, end up being captured in the anaerobic digestion and converted into energy. The avoided power generation represents a reduction of -46.24 kg $CO_{2\,eq}$ of global warming category emissions in scenario 1A, − 1.14 kg $CO_{2\,eq}$ in scenario 2A, and − 84.38 kg $CO_{2\,eq}$ in scenario 3A. As a result, all the energy use scenarios (1A, 2A, and 3A) have statistically lower impacts than their respective baseline scenarios according to the results of the modified NHST (Table 7.A in supplementary material).

In Brazil, animal waste management is responsible for 4.7% (27.2 Mt of $CO_{2\,eq}$) of the emissions of the livestock sector, with ruminant livestock, especially cattle, being the

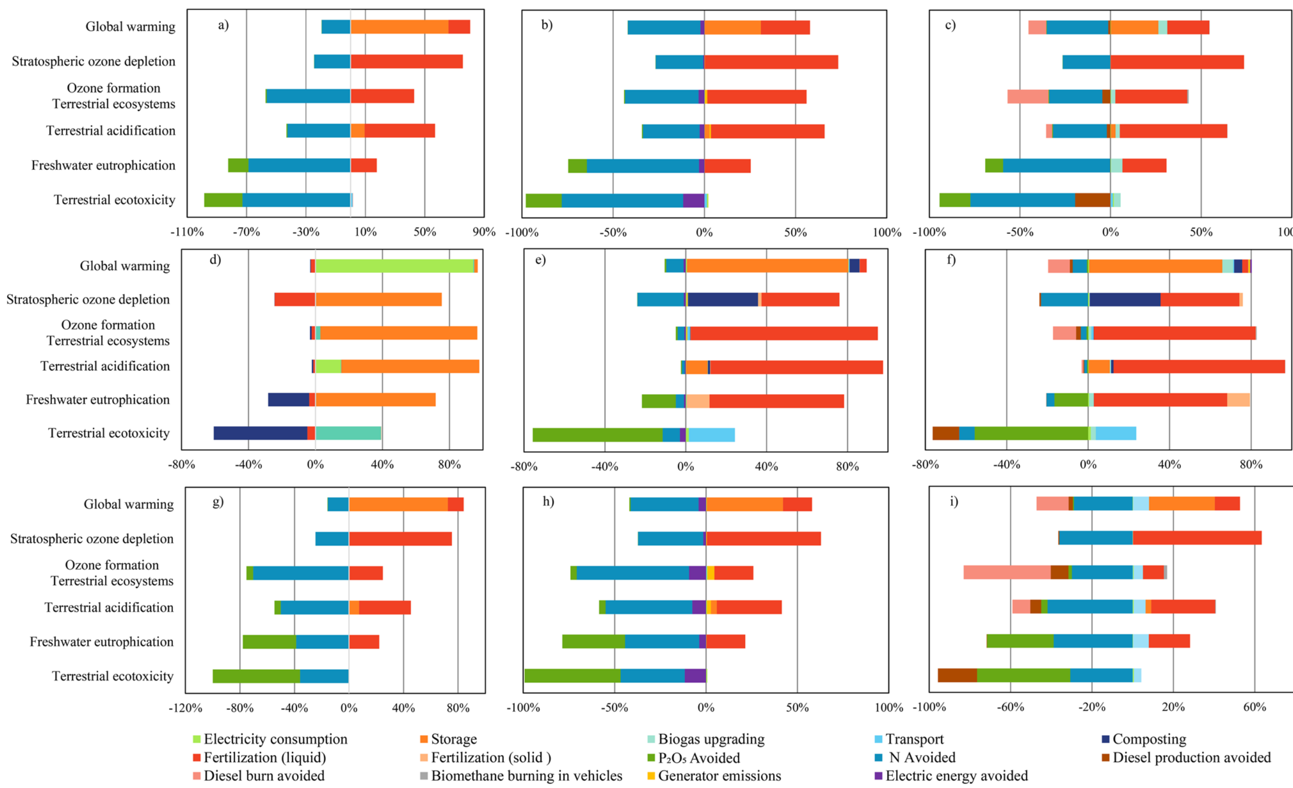

Fig. 2 Environmental impact assessment results for all scenarios. (a) BS1, (b) scenario 1A, (c) scenario 1B, (d) BS2, (e) scenario 2A, (f) scenario 2B, (g) BS3, (h) scenario 3A, and (i) scenario 3B. Results presented based on FU of 1 t of waste

critical activity, with 48.14 Mt of $CO_{2\ eq}$ from the use of beef cattle manure as fertilizer (Potenza et al. 2021). This demonstrates the importance of the sustainability of the production chain resulting from the adoption of management focused on the use of resources, given the significant contribution that the sector presents to the anthropogenic emission of GHG (FAO 2020; Hsu 2021).

For the stratospheric ozone depletion category, in the reference scenarios (BS1, BS2, and BS3), emissions from the biofertilizer application stage are the most damaging, equivalent to 75% of the damage category, as for the energy use scenarios (1A, 2A, and 3A), where the impacts of the stratospheric ozone depletion category, are also attributed mainly to the emissions from the application of the digestate on the soil, also by the emission of N_2O and the emissions from the fossil fuels needed for the transportation and disposal of the digestate. Ramírez-Arpide et al. (2018) also found that the transport step is a major contributor to stratospheric ozone depletion in the evaluation of anaerobic co-digestion of dairy cow manure due mainly to the emission of N_2O. According to Arunrat et al. (2021), the key to mitigating emissions lies in the more efficient use of resources. The authors found that minimizing transport was due to the farm's ability to produce its raw materials, which directly affected the environmental performance of the evaluated systems.

It is possible to verify that scenarios 1A and 3A present a lower impact than the respective reference scenarios (BS1 and BS3) in the stratospheric ozone depletion category. This is due to the lower energy demand of these plants and better biogas production, which make these scenarios stand out when compared to the reference scenarios, unlike scenario 2A, which has high energy demands in the plant and lower biogas production due to the characteristic of the manure, reducing the environmental benefits of this treatment unit. This corroborates the results presented in Table 7.A (in supplementary material), in which, due to the uncertainties in only 36% of the interactions, scenario SB2 is superior to scenario 2A, and they do not differ statistically.

By analyzing the other categories of impact, it is possible to verify that the stage of manure application to the soil is the critical stage in all scenarios. In addition to the categories already mentioned, this stage is also the most harmful in the formation of ozone in the terrestrial ecosystem (due to the emission of NOx), in terrestrial acidification due to the emission of ammonia, and in the category of freshwater eutrophication (due to the emission of phosphorus). In scenario 1A, fertilization accounts for 54%, 62%, and 25% of the impacts in the categories of ozone formation-terrestrial ecosystem, terrestrial acidification, and freshwater eutrophication, respectively. As a result, the impacts of these categories in scenario 1A do not differ statistically from the impacts observed in the SB1 (Table 7.A in the supplementary material).

In scenario 2A, the fertilizer emissions account for 93% (of the category ozone formation-terrestrial ecosystem), 86% (of the category terrestrial acidification), and 78% (of the category freshwater eutrophication). In scenario 3A, this step is responsible for the emission of 0.28 kg NOx, which represents 21% of the emissions in the category of ozone formation-terrestrial ecosystem, and the emission of $8.05 \cdot 10^{-3}$ kg P_{eq} equivalent to 21% of the impact of the category freshwater eutrophication. Although the baseline scenarios always performed better than the energy use scenarios in the freshwater eutrophication category, they do not differ statistically (Table 7.A in supplementary material). However, for the terrestrial acidification and ozone formation-terrestrial ecosystem categories, the difference is significant and favorable to scenarios 2A and 3A.

According to Styles et al. (2018), the fertilization stage is critical in terms of environmental damage. The benefits of replacing the use of commercial fertilizers do not always mitigate all the impact generated in the application stage because, in many cases, the application is performed in an agronomically inadequate way or associated with technologies that promote greater losses, such as sprinkling instead of incorporating the effluent, besides the transport over long distances for fertilization that contribute to reducing the benefits of adopting management focused on anaerobic digestion.

In general, it is possible to verify a negative impact on terrestrial ecotoxicity in all scenarios, especially due to nutrient recovery and the consequent avoided use of fertilizers, which promotes a greater environmental benefit than the impacts in this category. As a result, the values of the baseline scenarios do not differ statistically from the energy use scenarios, except for scenario 2A, where the results are better and differ statistically from SB2 (Table 7.A in the supplementary material). For Li et al. (2018), the avoided use of chemical fertilizers was responsible for 55–95% of the environmental credits of the ecotoxicity category in the scenarios of livestock waste management, and according to the authors, nickel (Ni) and mercury (Hg) are more ecotoxic and are commonly used in chemical fertilizers, which justifies the significant values in the mitigation of impacts. The main damage observed is due to the transport stage resulting from the use of fossil fuels and the emission of heavy metals present in the digestate that end up accumulating in the soil with fertilization.

Because of the significant influence of the fertilization phase, a sensitivity analysis was conducted to investigate the effects of varying emission factors on the performance of the impact categories studied. The highest sensitivities for BS1 were seen for the ozone formation-terrestrial ecosystem and terrestrial acidification categories, where changes

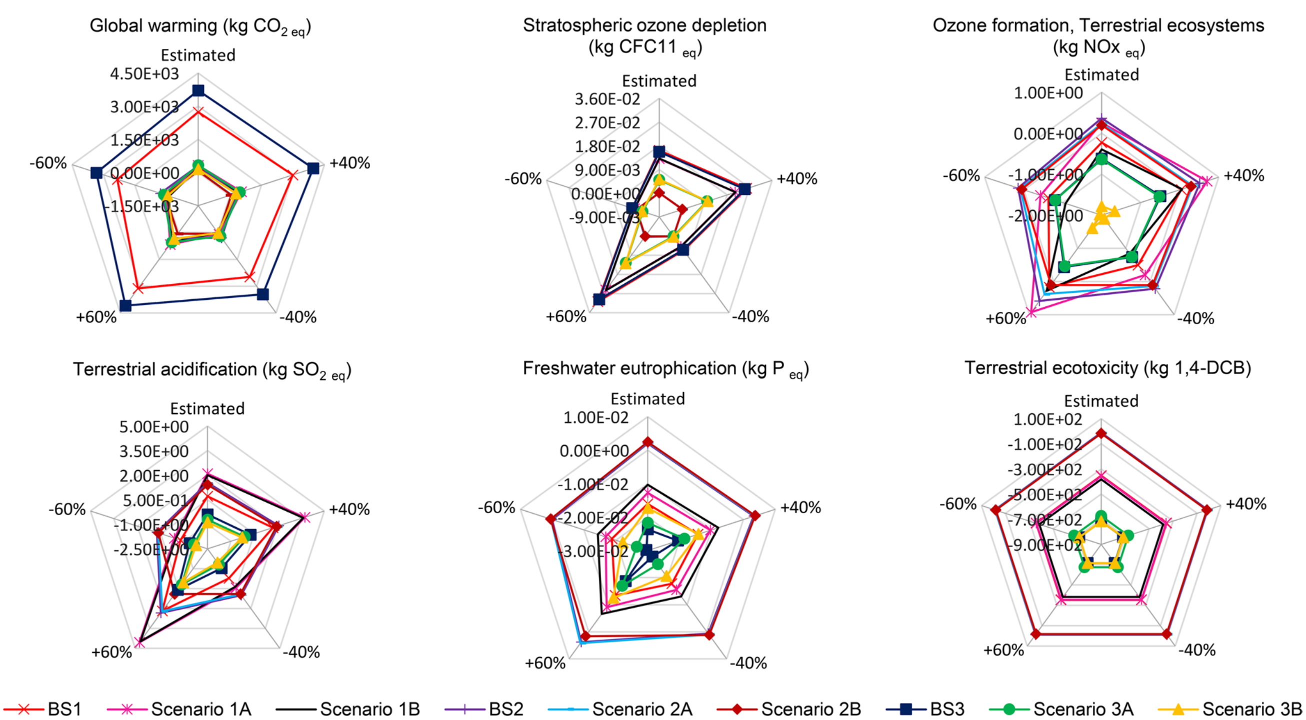

Fig. 3 Scenario (beef cattle, dairy, and sheep) sensitivity responds to different combinations of emissions in fertilization. Results presented based on FU of 1 t of waste

in emissions were able to affect up to 177% and 208% of the results, respectively (considering a 60% variation in emissions) (Fig. 3).

Besides this category, stratospheric ozone depletion also showed the largest deviations because the fertilization stage remained the most significant in terms of impacts, unlike global warming, which had a more pronounced effect on the storage stage, not suffering significant variation, with the change in emission rates of fertilization. For BS2, the greatest variation was for the stratospheric ozone depletion and freshwater eutrophication categories. With the reduction in rates (either 40% or 60%), emissions from the storage pond stand out, starting to affect terrestrial acidification significantly for this reference scenario (BS2). The BS3 scenario behaves similarly to changes in emission rates, with terrestrial acidification being the most sensitive category to change, with changes of up to 248% in category damages.

For scenario 1A, the greatest variations were found for the categories terrestrial acidification (118%) and stratospheric ozone depletion (270%) when the emission rate was altered by 60%, but in terms of significant steps, i.e., the process steps that contributed most to the result, they remained like those initially found. In 2A, the freshwater eutrophication (± 82%) was also affected more significantly, and with the reduction in emission rates of fertilization, composting became the most critical step in stratospheric ozone depletion, and the storage pond started to affect terrestrial acidification more significantly. In scenario 3A, terrestrial acidification and stratospheric ozone depletion were also the categories most affected by the changes; with a 60% reduction in fertilization emissions, the global warming potential is more significantly affected by the storage of digestate, accentuating the benefits of energy recovery.

The effect that the fertilization step has on the performance of the results is evident, so controlling the damage caused by this process is crucial for the viability of the nutrient recovery practice (Finzi et al. 2019). Thus, the adoption of the correct spreading technology is essential to minimize the losses to the environment, accentuating the benefits of energy recovery from waste through anaerobic digestion (Walling and Vaneeckhaute 2020).

Environmental performance of livestock waste management scenarios from the perspective of biomethane generation

In terms of the management of livestock waste for the use of biogas as a vehicular fuel, these scenarios stand out in comparison to the reference scenarios without the energy use of waste (Table 4.A in supplementary material). In general, the impacts are minimized from the perspective of biomethane generation in practically all the impact categories evaluated. In addition, for some categories, the treatment can produce environmental benefits greater than the damage generated in the scenarios.

In the global warming category, it is possible to verify that the use of biogas as biomethane promotes significant environmental gains in scenarios 1B, 2B, and 3B, compared to the reference scenarios (BS1, BS2, and BS3) (Table 7.A in supplementary material). The largest environmental benefits (avoided impacts) are from the avoided diesel burning steps, representing − 239.86 kg $CO_{2\ eq}$ for 1B, − 12.74 kg $CO_{2\ eq}$ for 2B, and − 427.98 kg $CO_{2\ eq}$ for 3B (Fig. 2(c), (f), and (i)). In addition, the avoided production of nitrogen fertilizer comes to represent a mitigation of − 33.93% of the damage in 1B, − 7.05% in 2B, and − 28.88% in 3B. It is notable the effect that the demand for fossil sources promotes in the performance of the scenarios in terms of GHG emissions, and betting on anaerobic digestion for livestock waste management using biogas as vehicular biomethane has a strong influence on the potential decarbonization of waste management and consequently the production chain (Mehta et al. 2022).

Regarding the harmful emissions in the global warming category, the largest contributions in all scenarios are from the storage pond emissions, representing 26.21% of the total impact (627.82 kg $CO_{2\ eq}$) in 1B, 66.41% (78.13 kg $CO_{2\ eq}$) in 2B and 32.32% (880.13 kg $CO_{2\ eq}$) in 3B. Scenarios 1B and 3B also have the stage of application of digestate to the soil as a potential source of emissions, corresponding to 26.21% and 12.32% of the damage, respectively. Scenario 3B has the steps of upgrading, compressing, and decompressing biomethane, representing 7.87% of the total impact, while in the other scenarios, the stage of purification of biogas is equivalent to 5% (in 1B and 2B) of emissions; this is because the PSA process is less efficient, promoting greater gas losses and consequently affecting the performance of scenarios (Kohlheb et al. 2021). According to Hiloidhari and Kumari (2021), the use of CO_2 can be an alternative to minimize the damage of the step of upgrading biogas; that is, it is necessary to maximize the use of resources to improve the environmental performance of treatment technologies.

In the stratospheric ozone depletion, ozone formation-terrestrial ecosystem, and terrestrial acidification categories, the soil application step of digestate is the most damaging in all scenarios. In 1B for stratospheric ozone depletion, the contribution of this step is $2.05 \cdot 10^{-2}$ kg $CFC11_{eq}$, equivalent to 73.55% of the damage. As well as in 3B, for this category, the application of digestate comprises the emission $1.24 \cdot 10^{-2}$ kg $CFC11_{eq}$ (63.22%). For 2B, besides the fertilization step, the emissions from the composting phase of the solid represent 38.01% of the emissions concerning stratospheric ozone depletion, so scenario 2B does not differ statistically from SB2 (Table 7.A in the supplementary material). Although the emissions from the composting, Awasthi et al. (2022) point out that the combination of anaerobic digestion and composting should be a prioritized model for the management of livestock waste since adding value to biofertilizers in solid form is more applicable due to the facilitation of transport and storage, which can contribute to the spread of the use of recovered composts.

The avoided burning of diesel contributes significantly to reducing the impacts of the terrestrial ozone-ecosystem formation category in all scenarios, mitigating 22.69% of the impacts in 1B, reducing $-3.43 \cdot 10^{-2}$ kg NOx $_{eq}$ in 2B and about −43% in 3B. There was a significant difference compared to the baseline scenarios, which had a higher impact of more than 96% of the time (Table 7.A in the supplementary material). Avoided diesel production and avoided vehicle diesel burning also contribute to reducing the impact of the terrestrial acidification category, especially in scenario 3B; together, they are equivalent to a reduction of $-2.00 \cdot 10^{-2}$ kg $SO_{2\ eq}$. This was more favorable in 96% of the iterations (Table 7.A in the supplementary material).

The high benefits of the use of biomethane as a vehicular fuel, according to Lyng and Brekke (2019), can be attributed beyond the replacement of fossil sources, in particular by the combination of better energy performance, with lower resource demands for the anaerobic digestion process; thus, according to the authors, biogas is the vehicle fuel with the best environmental performances compared to several other fuels not only from fossil sources but also from renewable sources.

The agricultural losses of phosphorus and nitrogen are already expected since the ion form of these nutrients in the liquid digestate is easier to leach and emit compared to fertilizers in solid form (Tian et al. 2021). Thus, the eutrophication, besides the losses of these compounds, suffered the influence of the upgrading phase, compression, and decompression of biomethane, being equivalent to 6.39% of the damage in 1B and 7.75% in 3B, but not so relevant in 2B, being the avoided use of P_2O_5 the most significant step in terms of mitigation for this category in this scenario, with a reduction of $-6.85 \cdot 10^{-4}$ kg P $_{eq}$. However, the scenarios did not differ statistically from the results of the base scenarios (Table 7.A in the supplementary material). In terms of terrestrial ecotoxicity in all scenarios, the benefits promoted by the avoided use of fossil products and fertilizers give the scenarios negative impacts; that is, promoting the practice of livestock waste treatment can mitigate impacts beyond those generated. Scenarios 1B and 2B are statistically more favorable than their respective baseline scenarios (Table 7.A in the supplementary material).

In terms of sensitivity of emissions from the fertilization process, the scenarios with biomethane generation behaved similarly to the scenarios with electricity generation since the fertilization stage is identical (with the same digestate), changing only the end use of biogas (Fig. 3). In all scenarios, the greatest sensitivities were verified for the categories of stratospheric ozone depletion, terrestrial acidification, and freshwater eutrophication, with the reduction or increase in emissions resulting from fertilization either compromising or considerably benefiting the results of the categories under study. Even with the reduction in emissions, fertilization was still configured as the most significant step for damage in virtually all categories, reinforcing the discussion already held about the importance of proper management of the process, so that the benefits of energy recovery are spared to the damage generated in the life cycle of waste treatment (Tian et al. 2021).

Electricity generation versus production of biomethane

Comparing the scenarios based on the use of the biogas given, that is, case A electricity and case B biomethane, it is possible to verify that the purpose given to the gas does not affect the environmental performance of the system, according to the impact categories evaluated (Fig. 4). In scenario 1, the generation of electric energy mitigates 88% of the impacts of beef cattle-raising residue management, while the generation of biomethane mitigates 92% of the impacts.

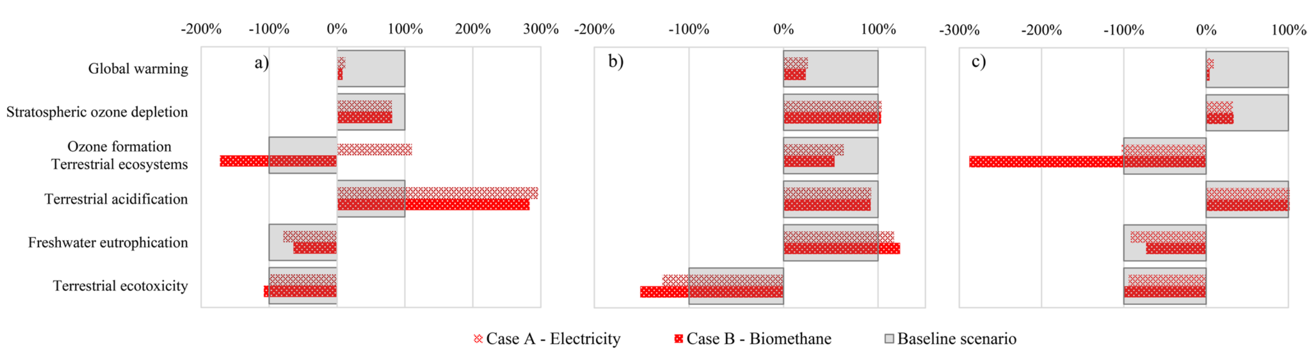

Fig. 4 Comparison of the results of the environmental impact assessment of the different scenarios against the baseline. (a) Scenario, (b) scenario 2, and (c) scenario 3

In scenario 2, referring to the management of milk cattle-raising residues, the energy use can be reduced by 74% and 76% of the impacts on the category, considering the generation of electric energy and biomethane, respectively. In all scenarios, the possibility of reducing the global warming potential is mainly related to the biogas generation capacity of the residues. Thus, as scenario 2 presents a lower gas generation, the performance of the categories is affected, with lower mitigated damages, which justifies the lower values compared to the other waste evaluated.

Scenario 3, which deals with the management of sheep farming waste, has for the generation of electric power a mitigation of − 3,372.65 kg of $CO_{2\ eq}$/t of waste digested (equivalent to a reduction of 91% of the impact), while the generation of biomethane results in mitigation of − 3559.09 kg of $CO_{2\ eq}$/t of waste digested (equivalent to a reduction of 96% of the impact). The higher mitigated values of GHG emissions from the perspective of biomethane generation, observed in all scenarios, are attributed to the reduction of dependence on fossil sources since the electricity generation considered the avoided production in the Brazilian context of electricity generation, which comes from renewable sources, especially hydroelectric basis, which reflects in the lower mitigated values (Ferrari et al. 2022).

Biomethane generation excels compared to electricity generation in the categories of ozone formation-terrestrial ecosystem and acidification. In these categories, the reduction in the use of fossil fuels (replacing diesel with biomethane) can promote a reduction in ozone formation-terrestrial ecosystem of − 72% for scenario 1B and − 188% for scenario 3B compared to the reference scenario. Analyzing acidification, on the other hand, scenario 3B was able to mitigate − 122% of the damage compared to BS3. In the other scenarios, the mitigation is lower due to the lower gas generation inherent to the characteristic of the waste. The co-digestion of manure with other organic sources can be an alternative to increase the environmental benefits of treatment systems, maximizing the production of biogas (Adghim et al. 2020).

Mehta et al. (2022) showed that the improvement in the potential for biogas generation due to the co-digestion of various manures (pig, cattle, and poultry) with grass silage doubled the potential for biomethane, significantly improving the environmental performance evaluated, reinforcing the importance of proper management and process optimization for the success of the treatment technology. Styles et al. (2022) point out that co-digestion is an environmentally favorable alternative if it is carried out considering the use of waste for this; the authors evaluated the use of energy crops to improve gas yield and found that environmentally, the burden of this practice was greater. Thus, the scenarios present possibilities for improvement, which can contribute to increased mitigation of emissions in manure management.

For the category of stratospheric ozone depletion, in scenario 2, the greater dependence on energy for plant operation due to the processes of scraping, separation, and composting makes the impacts generated higher than the reference scenario in both approaches of biogas use. The benefits generated were able to outweigh the category damages, with moderately superior performance in the for-power generation due to the non-release of harmful gases in the purification step from biogas to biomethane, which presents losses and demand for energy, affecting the category impacts.

According to Shinde et al. (2021), considering electricity generation with sources similar to fuel generation (in this case, fossil fuels), the use of biogas for electricity stands out since the emissions come only from the cogeneration unit, unlike biomethane, has high gas losses associated with high energy demand in the upgrading process, in addition to emissions from the use of biomethane in vehicles. However, both uses of biogas can assist in decarbonization by considerably reducing GHG emissions, which can be visualized in the results of this study. In addition, the charges of using the heat generated in the cogeneration units for heat and power were not considered to reduce the environmental benefits of electricity production, and CO_2 recovery in the biogas upgrade could improve the results of the scenarios, emphasizing that maximizing the use of resources should be prioritized (Cheng et al. 2020).

The losses from the PSA process are also reflected in the freshwater eutrophication results, with power generation excelling, which ended up having a higher emission than the baseline by 21% in scenario 1A, 17% in scenario 2A, and 8% in scenario 3A. Ioannou-Ttofa et al. (2021) investigated the environmental sustainability of Egyptian domestic digesters, and according to the authors, intentional biogas leaks/releases were also the main environmental focus. In addition to gas losses in the upgrading process, in anaerobic digestion systems, either in pipes or in the reactor dome, gas losses also occur, which compromise the environmental burden of the results (Baldé et al. 2022). Van den Oever et al. (2021), on the other hand, state that these values are not so expressive for new treatment plants and can be disregarded. In this sense, this is the main limitation of this work since fugitive emissions from the anaerobic digestion process were not considered, especially due to the lack of national data to assist in the estimates of these emissions, which may, in the end, reduce the benefits found.

In terms of terrestrial ecotoxicity, all scenarios are very similar, with negative values, including the baseline scenarios. This is because the most expressive stage of the category comes from the avoided use of nitrogen fertilizers, which ends up making the values of the base scenario very similar to those of energy use. The use of resources present in the waste is essential to close nutrient cycles and minimize losses, which is imperative for sustainable food production

(Wu et al. 2021). Thus, the promotion of technologies for the recovery and adequate use of these resources present in the residues is of extreme importance for the maintenance of world food production; the losses in the stage of application to the soil were expressive in several categories, which adds that the adequate management of the residues is fundamental for sustainability in the entire chain (Styles et al. 2018).

Sagastume Gutiérrez et al. (2022) discuss that in the agricultural context, especially in family farming, anaerobic digestion has an important social and economic role; the versatility of gas can affect the welfare of low-income citizens by using it to replace natural gas, an alternative use not explored in the current study but that has an important social role, minimizing costs with cogeneration units or gas upgrading, improving the viability and accessibility of the technology. Awasthi et al. (2022) also emphasize that the investments with the biogas generation units can be cushioned in the context of integrated plants, in which the residues from various sources and properties can be managed together, facilitating the adoption of the technology for producers of smaller production scale.

The use of biomethane as vehicular fuel has a high potential to neutralize the carbon of the residues of the cattle-raising chain, helping in the mitigation of GHG emissions. According to Sinigaglia et al. (2022), Brazil has one of the greatest potentials in the world in the generation of biomethane from waste, but the market related to biomethane is still incipient, there is no production of gas-powered vehicles, and the current fleet of vehicles powered by biomethane is not very significant, which opens the possibility for investments and studies to expand the sector considering the Brazilian potential. The generation of electricity through biogas also presents satisfactory results, demonstrating that the end use can be variable and adapted according to local needs.

Regardless of the final use of biogas, the benefits that anaerobic digestion promotes in environmental aspects in the management of livestock waste, the need to replace the use of fossil fuels is eminent, and energy recovery from waste proves to be an appropriate alternative for the closure of cycles in the management of livestock waste. Styles et al. (2022) emphasize that the care between the various variables present, i.e., between waste management, digestion and treatment processes, energy generation technologies, and land use, is the key to effectively delivering climate neutrality, which corroborates with the data presented in the present study.

Conclusions

Based on the results, the environmental benefits that the proper management of livestock waste presents are evident. Taking advantage of both the energy potential and the resources present in the waste can mitigate damage exceeding 100% in terms of global warming potential, regardless of the end use of biogas. The production of biomethane stood out with the lowest environmental charges compared to the generation of electricity but with very similar values for all the residues studied; thus, the choice is a function of the need for use. Proper management throughout the life cycle of livestock waste treatment is the key point to minimizing pollutant emissions, improving the circularity of production chains, and actively contributing to the decarbonization of the livestock sector.

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Declarations

Ethical approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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