Martín-Sanz-Garrido *et al.*
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Digestate from Spanish wholesale food markets: valorization as biofertilizer and analysis of environmental impacts compared to synthetic fertilizers

Carmen Martín-Sanz-Garrido[1,2], Marta Revuelta-Aramburu[1,2], Carlos Morales-Polo[1,2,3*] and Ana María Santos-Montes[1,3]

Abstract

This study presents a comprehensive environmental impact assessment of biofertilizers from digestate in Spain's 23 most extensive food markets using life cycle analysis. Eleven impact categories were evaluated. Results revealed significant variations in impacts across food markets, primarily due to differences in infrastructure sizing and energy self-sufficiency. Markets with appropriately sized anaerobic digestion facilities and energy self-sufficiency demonstrated significant environmental benefits, resulting in emission savings in 9 of the 11 impact categories assessed, except acidification and eutrophication. As a representative case of the markets with properly sized anaerobic digestion infrastructure and energy self-sufficiency, Market G as a representative market achieved up to 86% reduction in abiotic depletion and over 75% in toxicity categories. However, four food markets with either oversized or undersized infrastructure exhibited lower benefits, with Market A showing no advantages over synthetic fertilizers. In addition, the acidification and eutrophication categories posed challenges for all markets due to ammonia emissions during composting; in these impact categories, the values of biofertilizers are 5 to 8 times higher, depending on the market. When comparing unit and aggregate values (single scores), 19 out of 23 markets offer environmentally sustainable biofertilizers, resulting in an average emission savings of 55%. In conclusion, biofertilizers present a more sustainable alternative to synthetic fertilizers in most markets, contingent on adequate infrastructure and energy self-sufficiency. Future studies should focus on optimizing facility sizing and evaluating the influence of waste composition, as both factors significantly affect the environmental performance of digestate-based biofertilizers. This research highlights the potential of biofertilizers to contribute to more sustainable agricultural practices when the production process is well-optimized.

Keywords Anaerobic digestion, Digestate, Biofertilizer, Impact assessment, Waste valorization, Nutrient management

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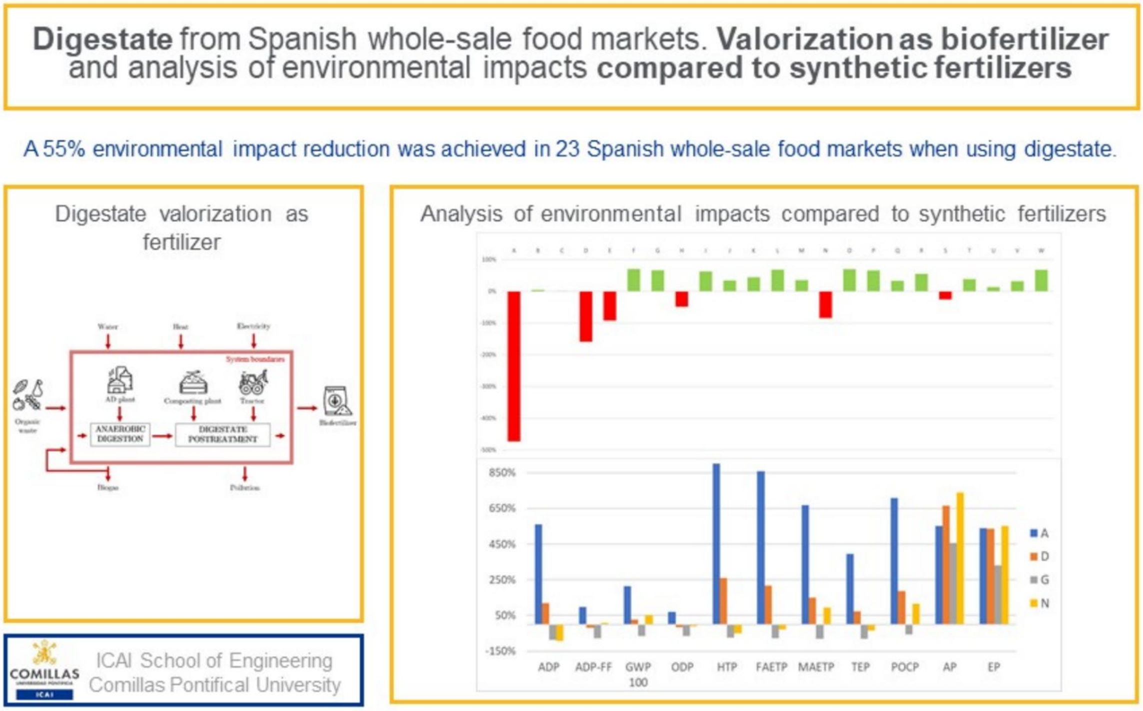
*Correspondence:
Carlos Morales-Polo
cmorales@comillas.edu
Full list of author information is available at the end of the article

Graphical Abstract



Digestate from Spanish whole-sale food markets. **Valorization as biofertilizer** and analysis of environmental impacts **compared to synthetic fertilizers**

A 55% environmental impact reduction was achieved in 23 Spanish whole-sale food markets when using digestate.

Background

Greenhouse gas emissions are the primary driver of global climate change, generating worldwide concern. Among the multiple areas impacted by this, organic waste management has gained increasing attention due to its potential to reduce emissions. The United Nations Global Waste Management Outlook estimates that improved solid waste management, including recycling, diverting waste from landfills, and recovering energy from waste, could decrease global emissions by 15–25% [1]. Recent research supports the role of effective waste management in reducing emissions [2]. While municipal waste management has been a primary focus, the food industry is an often-overlooked significant contributor to waste production [3]. The agri-food sector, the third largest in economic terms in Europe and second globally, generates a considerable amount of waste. Notably, 13% of food is lost in the supply chain, and 19% is wasted at the household, food service, and retail levels, according to the Food and Agriculture Organization (FAO) in 2022 [4].

In Spain, wholesale markets are key waste generators, producing around 83,000 tons annually of both organic and inorganic waste [5]. The challenge lies in transforming this waste into valuable resources, such as biogas, through anaerobic digestion (AD). AD is a biological process where micro-organisms break down organic matter without oxygen, resulting in biogas—a mixture of hydrogen, methane, and carbon dioxide—and digestate, a solid–liquid residue [6]. AD helps address climate change by mitigating emissions while promoting effective waste management practices. As demonstrated by [7], the food industry's waste management is a critical research niche due to its environmental impacts and opportunities.

AD has become a vital tool for managing organic waste in the food industry, converting waste into energy and valuable by-products [8–10]. One of these by-products, digestate, is rich in nutrients, such as nitrogen, phosphorus, and potassium, making it suitable for use as a fertilizer [11]. However, managing large quantities of digestate has become challenging [12], and optimizing biogas production and digestate utilization is crucial. Digestate can be valorized as fertilizer, improving soil quality by gradually releasing nutrients [13], thus reducing dependence on commercial fertilizers, often contributing to soil degradation.

The environmental benefits of using digestate over traditional composting methods have been documented.

For instance, [14] found that composting digestate has a lower environmental footprint than direct composting. In addition, applying digestate to soil enhances crop yield and productivity, as shown by [15], with the added advantage of increasing soil organic carbon and improving crop nitrogen utilization [16]. This dual benefit of improving soil quality while reducing chemical fertilizer use is particularly relevant in light of current global agricultural challenges. This integration of digestate into agricultural systems promotes a circular bioeconomy in the food sector, offering environmental and economic advantages [17]. Digestate applications contribute to long-term sustainability in agricultural practices by reducing reliance on non-renewable resources.

Despite these benefits, the widespread adoption of digestate as a biofertilizer faces several challenges. It is essential to conduct a thorough assessment of the impacts associated with producing biofertilizers from digestate. Comprehensive studies can evaluate their effectiveness and sustainability compared to synthetic fertilizers with similar nutritional compositions. This approach will also facilitate informed decision-making [18]. Overcoming these barriers requires further scientific investigation into the efficiency of digestate in various agricultural systems and climates.

Life Cycle Assessment (LCA) studies have been crucial in comparing the environmental impacts of digestate-derived and commercial fertilizers. LCA is widely acknowledged as a comprehensive tool for assessing the environmental sustainability of waste management processes [19]. Various studies have used LCA to evaluate impacts across different digestate treatments: [20] evaluated low-cost technologies, such as vermifilters and sand filters, while [21] compares the environmental benefits of direct digestate application and biofertilizer production. Further, [22] explored various forms of biofertilizers, such as pellets, liquid fertilizers, and biocompost. Other studies have examined the integration of AD with alternative processes such as vermicomposting [23] or hydrothermal carbonization [24] to enhance digestate utilization. Eco-industrial systems combining micro-scale AD with solid-state fermentation have also been analyzed [25], and the impacts of different digestate treatment methods have been evaluated by [26]. These assessments provide critical insights into managing digestate, ensuring minimal environmental impact while maximizing resource recovery.

Given the environmental importance of managing food waste and the usefulness of LCA in assessing waste treatment methods, this research aims to compare the environmental impacts of biofertilizers derived from digestate with those of NPK-type inorganic fertilizers. Using data from wholesale markets, this study evaluates the sustainability of digestate-derived fertilizers versus conventional alternatives. In addition, it quantifies the level of integration of digestate into the circular economy, positioning it as a sustainable and viable alternative to traditional fertilizers. This analysis is crucial for guiding future policy decisions and encouraging the adoption of bio-based solutions in agricultural practices.

Materials and methods

This manuscript evaluates the environmental impact of biofertilizer production from digestate generated by AD of waste from wholesale markets in Spain, using LCA methodology. The LCA follows ISO 14040 and 14044 standards [27, 28], and the LCA model was built using SimaPro 9.5.0 software and the Ecoinvent database version 3.8 was used with the 'cutoff' system model (cutoff by classification), consistent with the attributional nature of the study. Environmental impacts, including Global Warming Potential (GWP), were calculated using the CML-IA baseline V3.07/EU25 method, with IPCC 2021 factors as the baseline for GWP.

Goal and scope

This LCA aims to determine the environmental impacts of organic fertilizer production from digestate generated by wholesale agri-food market waste, and to compare these impacts with those of synthetic fertilizers with same NPK content. In doing so, it also explores how variations in the composition and quantity of waste influence the performance of the resulting biofertilizer. This variation allows the study to fully understand how different waste types can influence biofertilizer production and its related environmental burdens.

Function and functional unit

The LCA is attributional, isolating the biofertilizer process from the broader economy with clear system boundaries. All impacts are referred to the functional unit, which is 1 kg of biofertilizer produced from digestate at the end of the production process. This choice of functional unit reflects the primary purpose of the study: to evaluate the biofertilizer's environmental performance relative to its production scale. However, it is acknowledged that the nutrient content (N, P, and K) of each biofertilizer varies depending on the waste composition of each food market. When comparing with synthetic fertilizers, mineral fertilizers with matching NPK compositions were selected to ensure functional equivalence in that comparison. Therefore, this functional unit does not reflect equivalent fertilizing function across all cases. The agronomic behavior of these biofertilizers, including nutrient release and soil performance, will be addressed in future research.

System boundaries

Figure 1 outlines the system boundaries, including the input of organic waste to the digester upstream and biofertilizer production downstream. The system boundaries were explicitly designed to exclude certain stages, like transporting raw organic waste to the digester, assuming all processes occur within the market premises. This further narrowed the environmental focus to the production activities. The Life Cycle Inventory (LCI) starts with the entry of waste from wholesale markets without considering its prior production or transport and ends with the production of biofertilizers. Post-application impacts of biofertilizers are excluded.

During the AD phase, only digester operation flows are considered. Recharge activities and transportation of organic waste and digestate are excluded since the digester is assumed to be on-site. Notably, transportation of the digestate for post-treatment is not considered due to the proximity of the treatment facility. Only air emissions from AD and post-treatment processes are included. The study assumes that AD and digestate post-treatment occur in certified plants with leak prevention systems and wastewater treatment facilities, preventing pollutant emissions into the soil or local water [29].

Life cycle inventory (LCI)

The LCI compiles all the processes necessary to produce the functional unit. The inventory is divided into two main processes: anaerobic digestion of organic waste and digestate post-treatment (composting). Figure 2 shows the inventory structure established for this study, according to the levels of importance of the production flows of the processes involved in obtaining the biofertilizer.

Anaerobic digestion (AD)

The process flows considered for the LCA inventory are as follows (a brief explanation of each flow is given below, and concrete quantities and qualities of each are analyzed in the study for each of the 23 cases treated):

The organic waste from the food market is the primary input of the anaerobic digester. For each market,

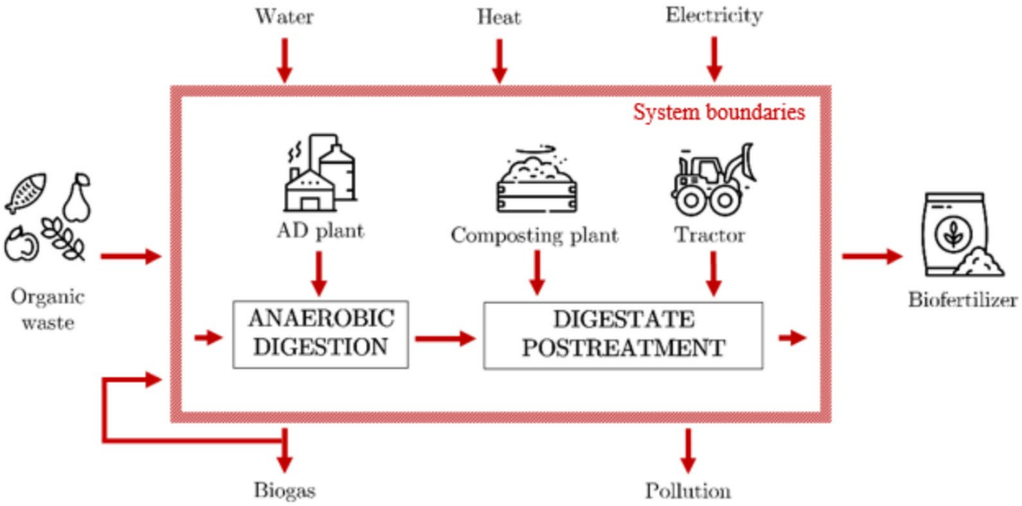


Fig. 1 System boundaries of the proposed LCA

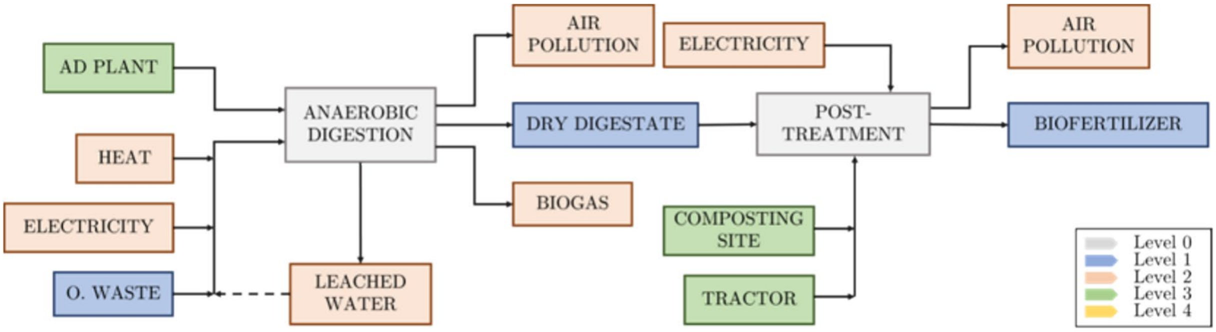


Fig. 2 Life cycle inventory structure

the waste assigned is the actual quantity and mixture of organic waste (meat, fish, vegetables, and fruit) produced annually at the 23 largest food markets in Spain. Table 1 shows the total quantities of usable waste broken down by nature (meat, fish, fruit, and vegetables)—each of the 23 food markets has been anonymized and identified by a letter (Market A to Market W) to facilitate comparative analysis while preserving confidentiality. Water is added to adjust the moisture of incoming waste, and a 30% recirculation of the liquid fraction of the digestate is used [30, 31]. The recirculation of the liquid fraction not only optimizes water use within the system but also stabilizes the digester's pH and temperature.

A standard digester with a 500 m^3 capacity and a 20-year lifespan is modeled. The total impacts of construction and operation are allocated based on the total biofertilizer produced. This amortization ensures that all resource-intensive phases of the digester's lifecycle are appropriately weighted relative to the amount of biofertilizer output. The study calculates biogas production for the 23 cases based on experimental data from [5]. Biogas production per ton of waste is 9.13 Nm^3 for vegetables and fruits residue (V), 13.3 Nm^3 for meat residue (M), and 7.69 Nm^3 for fish residue (F). The biogas' CH_4 content varies significantly between substrates, reflecting the distinct biochemical properties of the input materials. CH_4 content is 32.25% for V, 21.02% for M, and 13.68% for F. Currently, anaerobic digesters are oriented towards energy self-sufficiency, which means that a part of the biogas generated is used as fuel for the plant's electricity and heat needs. At the same time, the surplus is considered as the net energy produced by the system [32]. For each market, the heat and electricity needs are calculated using the hypotheses presented in [5].

Digestate is a critical by-product, and its quality influences the overall performance of the biofertilizer. The digestate quantity and composition per ton of input waste have been determined experimentally for each waste fraction. The digestate composition was calculated for each market by considering the amount of each generated waste fraction. In addition, a 30% reduction of the liquid fraction was applied for water recirculation. Specifically, the following experimental methods have been used: humidity and dry mass are determined by gravimetry following the APHA 2540-G method [33]. The pH of the substrates is determined by direct measurement of the sample following the APHA 2320-B method [33]. Total Organic Carbon (TOC), has been determined following the open reflux method APHA 5310 [33]. The elemental analysis of the digestate has been carried out using LECO CHNS "TruSpec Micro" CHNS equipment.

The experimental data of the digestate produced as a function of the amount of incoming substrate in each market, and its composition are shown in Table 1.

The process used is considered to recover all gases leaving the digester for use as biogas. However, any biogas leakage from the process at all stages is considered an emission, for which the quantities given in [29], which collects fugitive emissions data from methanation plants in the United Kingdom, have been used. This study references a leakage value of 2.3% of the total gas generated.

To ensure methodological consistency across all 23 markets, infrastructure impacts for the anaerobic digestion plant were calculated based on the Ecoinvent process "Anaerobic digestion plant, agriculture, with methane recovery (CH) construction cutoff." This process includes the full construction life cycle of the plant, covering raw material extraction, component manufacturing, and on-site assembly, using materials, such as concrete, steel, PVC, and wood. A common plant configuration was assumed with a 20-year lifespan and a 500 m^3 digester, which reflects typical small-to-medium European agricultural facilities. The total environmental burden associated with construction was amortized over the volume of organic waste treated throughout the plant's lifetime and then allocated to each kilogram of biofertilizer produced. This approach allows for a fair and consistent comparison between markets and avoids overestimating infrastructure impacts for low-output systems.

Post-treatment: composting

The digestate from AD has a high moisture content and is further processed through composting, a biological process to stabilize organic waste for soil application. The quantity and composition of digestate are tailored for each of the 23 cases. The mass of digestate entering the composting process is calculated after applying the internal recirculation adjustment described in the anaerobic digestion stage. The composting process emissions are based on Ecoinvent's database for open-air composting facilities. Since composting facilities are typically open-air, all process emissions are assumed to be directly emitted into the atmosphere. It should be noted that this generic emission profile does not account for variations in digestate composition between markets. This simplification may affect the accuracy of some impact categories and is acknowledged as a limitation of the current study.

To calculate impacts due to infrastructure, the same procedure used in the infrastructure of the AD plant impacts is applied: all construction and operation costs throughout the plant's lifecycle are divided by the total production of biofertilizer, thus obtaining the environmental amortization of the composting plants.

Table 1 Composition and production data of substrate, biogas, and digestate in anaerobic digestion

	Substrate				Biogas		Digestate											
	Inlet	Composition			Gross production	Net production	Production	Composition										
		V (%)	M (%)	F (%)				pH	Dry mass	Hum	TOC	N	P	K	S	Ca	Mg	Fe
	Ton/year				Nm^3/year		Ton/year		%	g/kg_{db}								
A	1.8	0	0	100	13.7	− 7.6	1.2	9.1	40	730	74	150	6	26	0	6	5	3
B	138.7	100	0	0	1267.0	515.3	92.5	6.3	60	666	255	20	3	31	2	12	5	6
C	129.0	100	0	0	1177.9	480.9	86	6.3	60	666	255	20	3	31	2	12	5	6
D	9.9	61	0	39	84.8	20.8	6.6	7	50	691	184.4	70.7	4.2	29.1	1.2	9.7	5	4.8
E	9302.8	62	11	27	79,872.4	− 52,120.4	6201.9	6.7	50	662.4	216.7	59	4.1	32	3.8	11.9	5.6	4.6
F	585.0	64	0	36	5036.4	676.5	390	6.9	50	689	189.8	66.8	4.1	29.2	1.3	9.8	5	4.9
G	147.8	50	0	50	1243.3	167.0	98.5	7.2	50	698	164.5	85	4.5	28.5	1	9	5	4.5
H	57.0	100	0	0	520.8	218.9	38	6.3	60	666	255	20	3	31	2	12	5	6
I	199.7	60	0	40	1708.3	333.8	133.1	7	50	691.6	182.6	72	4.2	29	1.2	9.6	5	4.8
J	70.2	68	0	32	608.4	164.9	46.8	6.9	50	686.5	197.1	61.6	4	29.4	1.4	10.1	5	5
K	76.8	65	0	35	662.3	167.5	51.2	6.9	50	688.4	191.7	65.5	4.1	29.3	1.3	9.9	5	5
L	865.4	62	11	27	7430.2	638.1	576.9	6.7	50	662.4	216.7	59	4.1	32	3.8	11.9	5.6	4.6
M	72.5	71	0	29	631.9	183.8	48.3	6.8	50	684.6	202.5	57.7	3.9	29.6	1.4	10.3	5	5.1
N	13,003.5	57	9	34	110,670.7	− 81,029.0	8669	6.8	50	670.7	202.1	67.4	4.3	31.2	3.2	11.2	5.5	4.5
O	500.4	65	0	35	4317.0	696.5	333.6	6.9	50	688.4	191.7	65.5	4.1	29.3	1.3	9.9	5	5
P	502.1	62	11	27	4310.5	710.1	334.7	6.7	50	662.4	216.7	59	4.1	32	3.8	11.9	5.6	4.6
Q	621.5	89	11	0	5578.6	1626.3	414.3	6.2	60	645.1	265.6	23.9	3.3	33.3	4.3	13.5	5.6	5.5
R	161.4	66	0	34	1393.9	334.6	107.6	6.9	50	687.8	193.5	64.2	4	29.3	1.3	10	5	5
S	76.6	100	0	0	699.2	291.6	51	6.3	60	666	255	20	3	31	2	12	5	6
T	1392.3	62	11	27	11,953.8	− 341.2	928.2	6.7	50	662.4	216.7	59	4.1	32	3.8	11.9	5.6	4.6
U	183.2	100	0	0	1673.2	667.8	122.1	6.3	60	666	255	20	3	31	2	12	5	6
V	549.5	100	0	0	5018.0	1692.5	366.3	6.3	60	666	255	20	3	31	2	12	5	6
W	805.4	62	11	27	6915.06	683.64	536.9	6.7	50	662.4	216.7	59	4.1	32	3.8	11.9	5.6	4.6

Ecoinvent's infrastructure is used, with an annual capacity of 10,000 tons and a useful life of 20 years.

In composting, it is necessary to stir the substrate frequently to provide oxygen to the micro-organisms. This aeration is carried out with a diesel-powered mechanical shovel, and the amortization and emissions depend on the amount of digestate treated. Since the tractor is not standardized, this study will use the time and type of tractor specified in the Ecoinvent 3 database for 1 ton of composted substrate. The tractor used will be diesel, with a power of ≥ 74.57 kW, a low load factor, and a use of 3.52 h for each ton of waste treated. Information from the Ecoinvent 3 database will be used to estimate an electricity consumption of 11.8 kWh per ton of substrate.

For each market, a mass balance of the composting process has been carried out, thus obtaining the amount and composition of the resulting biofertilizer. Once the quantities and qualities of each process flow have been detailed according to the market to be analyzed, the life cycle inventory has been built in Simapro according to the structure presented in Fig. 2.

The atmospheric emissions produced by composting per amount of digestate treated have been established according to the emissions set by the Ecoinvent library for composting processes. Since composting is generally carried out in open facilities, all these generated emissions are emitted into the atmosphere.

Synthetic fertilizers

Based on Ecoinvent, the impacts of 5 types of NPK inorganic fertilizers have been simulated, with compositions like those of biofertilizers.

Life Cycle Impact Assessment (LCIA)

For Life Cycle Impact Assessment (LCIA), the CML-IA baseline V3.08/EU25 method, developed by Leiden University, has been selected, and it evaluates 11 impact categories at the midpoint. This method is preferred due to its rigorous methodology and constant updating. The global warming potential has been evaluated using the IPCC/year method with a time horizon of 100 years. The eleven categories are Global warming potential (GWP 100), Abiotic depletion potential (ADP), Abiotic depletion potential fossil fuels (ADP-FF), Acidification potential (AP), Eutrophication potential (EP), Ozone depletion potential (ODP), Photochemical oxidation potential (PCOP); Human toxicity potential (HTP); Terrestrial ecotoxicity potential (TETP); Freshwater aquatic ecotoxicity potential (FAETP); Marine aquatic ecotoxicity potential (MAETP).

Separate LCAs are conducted for different categories of organic waste, recognizing that the digestate's properties vary significantly based on the type of waste used in AD. This differentiation allows the study to provide more nuanced insights into the environmental impacts, particularly in light of how different waste types generate varying volumes of digestate and biogas. This allows for a more accurate assessment of environmental impacts associated with biofertilizer production, providing valuable insights for agricultural decision-making and environmental management.

An economic allocation was applied to assess the impacts of biogas and digestate, the two AD products. A biogas price of €0.312/Nm^3 and €4/ton for digestate was used, assigning a weight of 43–47% to digestate across the 23 markets according to the calculations of [34]. The allocation approach accounts for the relative economic value of biogas versus digestate, ensuring the impacts are proportionally distributed between these two co-products. It should be noted that the choice of economic allocation, while commonly applied in LCA studies, can affect the relative weighting of impacts assigned to biogas and digestate. Variations in market value assumptions may therefore influence the interpretation of environmental burdens.

Results and discussion

Based on 23 cases, this study's results are presented in two phases. In the first phase, the 11 environmental impact categories were quantified using the CML–IA method. In the second phase, the sustainability of the biofertilizers was assessed by comparing these impact results with the LCA of inorganic fertilizers with the same composition. This comparison highlights critical differences in environmental performance, providing a clearer understanding of the potential advantages of biofertilizer use.

Environmental impact assessment of processes

The analysis of the 23 markets (labeled A to W) in Fig. 3 presents the contribution to global warming potential, measured in CO_2 equivalent emissions, presenting the direct environmental impacts associated with the production of 1 kg of biofertilizer in each market, with no system expansion or avoided burdens included. After obtaining the results for each case, a comparative assessment by impact category was conducted to evaluate how variations in the quality and quantity of organic waste influence the outcomes. The impact of global warming potential (Fig. 3a) has been taken as an example of what happens with the other impact categories so that with this impact, the influence of the structure is studied.

The results can be classified into three categories according to the GWP value in kg CO_2 eq per kg of fertilizer: high, with values higher than 2.5, as observed in market A; intermediate, with values between 0.7 and 0.5

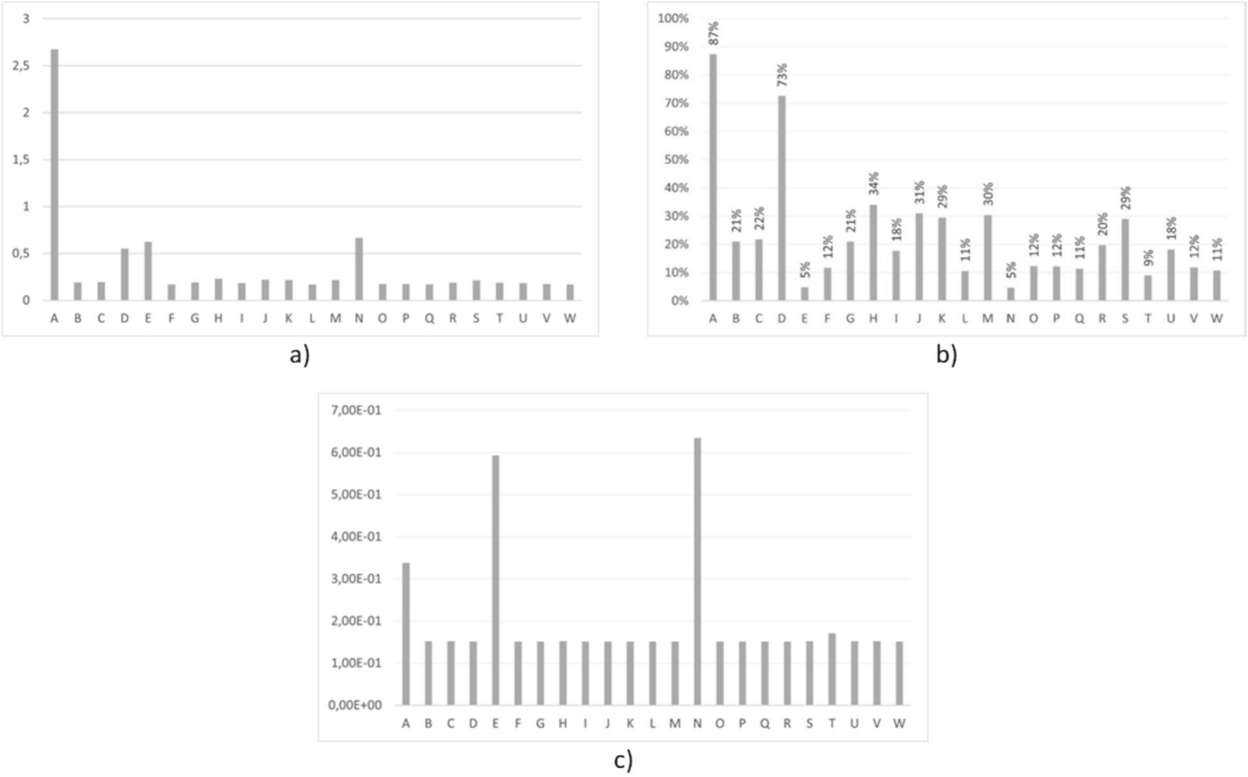


Fig. 3 Global warming potential results per market. **a** Global results (kg CO_2 eq); **b** percentage of result derived from infrastructure (%); **c** Results excluding infrastructure (kg CO_2 eq)

for markets D, E and N; and low, with values lower than 0.23, which is the maximum value for those markets. On analyzing these results in detail, it was found that the values depended on the qualities and quantities of organic waste and the design of the infrastructure used in the study, which is repeated for the other impact categories. The global warming potential of market A is up to 11 times higher than that of the different markets. This result is due to an oversizing of the anaerobic digestion infrastructure, causing a higher infrastructure amortization impact per kg of biofertilizer produced.

Also noteworthy is the impact of the under-sizing of infrastructure in markets E and N, which, due to the large influx of waste from food markets, does not generate enough biogas for anaerobic digestion to be self-sufficient. A priori, they present a lower proportional impact of infrastructure, which would have given a better result. However, the impacts derived from the fossil proportion of the national electricity mix contribute an equivalent CO_2 that triples the results of the other markets. We can find the remaining 19 cases at a lower level, which present the same results except for small differences in sizing.

Influence of the results on infrastructure sizing

Given the impact on the results observed due to the over or under-sizing of infrastructure, an analysis of the results obtained for the 11 impact categories has been carried out, analyzing the results obtained if the infrastructure is excluded from the processes and the impact per impact category that these have in each of the 23 cases.

Figure 3b clearly shows the percentage of infrastructure-only derived impacts in the category of global warming potential, where infrastructure alone makes up almost the total impact obtained for markets A and D and only 5% for markets E and N. This phenomenon occurs, albeit at different scales, in the rest of the impact categories studied, and it validates the hypotheses formulated in the first stage of the interpretation of results.

This observation highlights that infrastructure sizing strongly influences environmental performance indicators. While digesters cannot be resized in practice once built, modeling their performance under adjusted sizing conditions provides useful insights into the sensitivity of the results and the importance of appropriate design at the planning stage.

Result analysis excluding infrastructure impacts

In light of the overall result distortion caused by the imposition of a standard infrastructure across all 23 food markets, a third stage of results analysis excluding the impacts derived from infrastructure has been performed, which is represented in Fig. 3c shows that, once the infrastructure impacts have been removed, all food markets score the same results except for those that are not self-sufficient (i.e., do not produce enough biogas to cover their electric and heat demand).

The extra potential for global warming observed in these four markets is directly derived from the environmental impacts of the Spanish electricity mix (the non-renewable part) from which they source their electricity and heat needs. Moreover, it can be observed that the final score in this category is directly proportional to the amount of electricity demanded from the grid, as market N demands 16 more times the energy that market T imports from the grid for each kg of biofertilizer produced.

It is also interesting to note that the remaining 19 markets have almost the same result for this category. This is because, by eliminating the oversizing of the infrastructure and using a functional unit of 1 kg of biofertilizers to reference the results, the only differentiating factor between the different markets is the mixture of meat, fish, fruit and vegetable waste at the inlet of the anaerobic digester. As all these types of organic wastes are considered waste in the life cycle inventory, the LCA methodology assigns them a null environmental impact upstream, thus having no impact on the results of the environmental impact assessment. This makes the amount of biogas produced by each market the only differential factor between the obtained results of the different self-sufficient markets.

Results in the other impact categories

Results have been obtained for each of the 11 impact categories analyzed, excluding the influence of the structure, and are shown in Fig. 4.

The impact categories with a behavior similar to GWP 100 are ADP, ADP-FF, ODP, PCOP, HTP, TETP, FAETP and MAETP. These categories have high impact values for the E and N markets, intermediate values for market A, and low values for the rest.

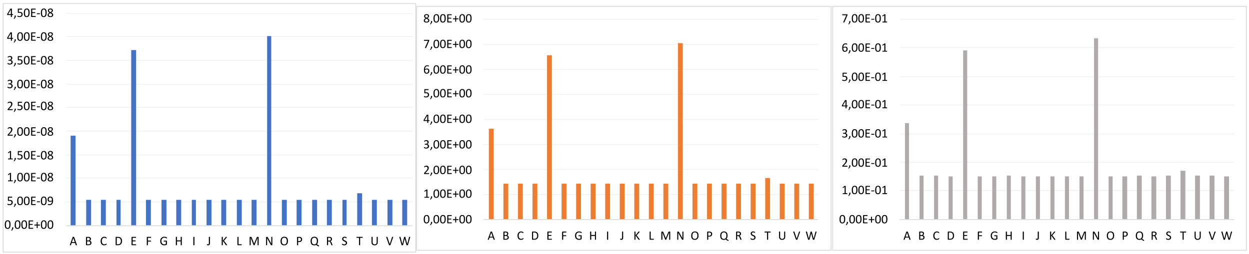
Once again, it is important to note that markets with higher energy demands have a significantly higher environmental impact in these categories, similar to what was discussed for the category of GWP. In the case of market A, which treats a small amount of waste, the high impact in all categories is due to the infrastructure and the composition of the digestate, as it only treats fish waste, leading to a lower amount of biogas produced.

The impact in these categories primarily depends on the materials, fuels, and processes used to build the infrastructure and the demand for electricity and heat from the grid in the after-treatment and AD processes. On the other hand, the rest of the cases present uniform results across all categories, demonstrating that impact variations are more influenced by infrastructure design and capacity than other factors.

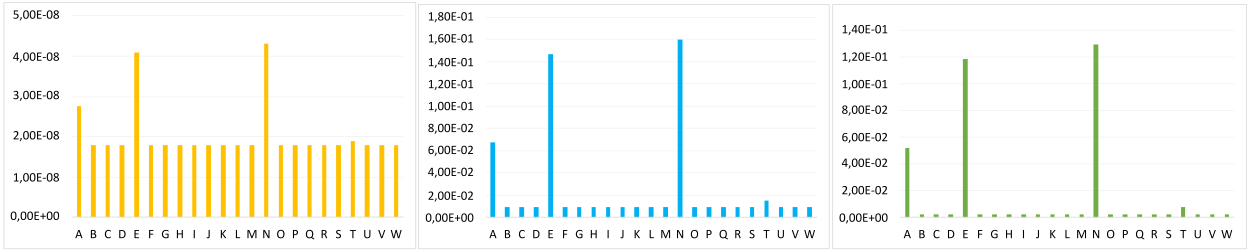
As for the categories of acidification and eutrophication, the behaviors are different. Infrastructure contribution is small in both cases, and processes are primarily responsible for emissions. In all cases, the pollutant that contributes most to acidification is ammonia (NH_3) emitted during digestate composting (98% in self-sufficient markets and 81% in dependent markets), followed by SO_2 and NOx derived from the use of electricity and combustion in the diesel engine (which contribute the remaining 2% and 19% in each case). This analysis is based on the calculations made by the CLM-IA method in Simapro, which assigns to the NH_3 a characterization factor of 1.6 kg of SO_2 equivalent. In this model, gases contributing to acidification, such as NOx and SO_2, are considered alongside other compounds. Still, ammonia stands out as one of the leading agents due to its ability to form secondary aerosols, such as ammonium nitrate and ammonium sulphate [35]. Concerning eutrophication, ammonia is one of the main compounds responsible. Ammonia is released during composting of digestate, and its high nitrogen concentration acts as a key nutrient in aquatic ecosystems. This excess of nutrients promotes the uncontrolled growth of algae, which can lead to hypoxia or the reduction of oxygen in the water, seriously affecting aquatic life and water quality [36].

Comparison of the results of biofertilizer LCA to synthetic fertilizers

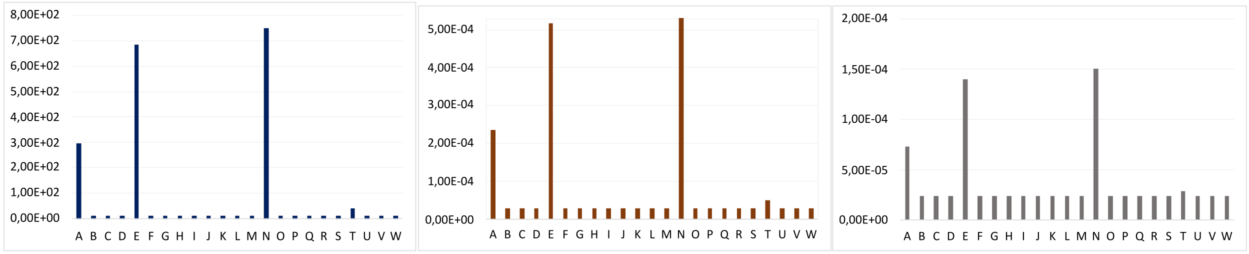
To be able to effectively compare the biofertilizer with the commercial fertilizers generally used in agriculture, and thus to be able to evaluate them as a sustainable alternative, they must have the same NPK content (as a difference in composition can result in a substantial difference in the results of the LCA). For this reason, each biofertilizer will be compared with an NPK fertilizer (containing nitrogen, phosphorus, and potassium) of the same composition. It is important to note that these inorganic fertilizers have tailor-made compositions that allow them to be compared correctly with the biofertilizers on the market. However, none of them have an inorganic fertilizer composition common in agriculture. In the future, to obtain a biofertilizer composition to replace common



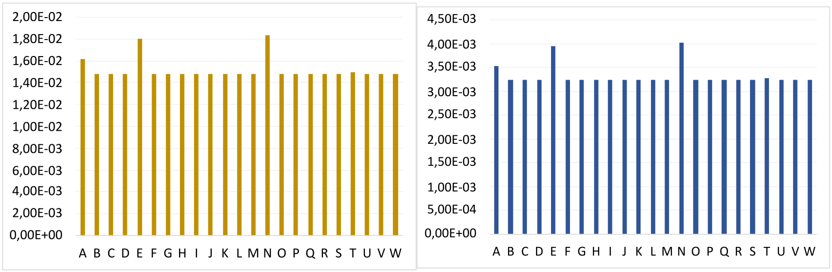
a) ADP b) ADP-FF c) GWP 100



d) ODP e) HTP f) FAETP



g) MAETP h) TEP i) POCP



j) AP k) EP

Fig. 4 Results for different environmental impact categories in each market. **a** Abiotic depletion (kg Sb eq); **b** abiotic depletion—fossil fuels (MJ); **c** global warming potential (kg CO_2 eq); **d** ozone layer depletion (kg CFC-11 eq); **e** human toxicity (kg 1,4-DCB eq); **f** freshwater ecotoxicity (kg 1,4-DCB eq); **g** marine ecotoxicity (kg 1,4-DCB eq); **h** terrestrial ecotoxicity (kg 1,4-DCB eq); **i** photochemical oxidation (kg C2H4 eq); **j** acidification (kg SO2 eq); **k** eutrophication (kg PO4 eq)

fertilizers, it will be necessary to vary the percentages of each substrate at the input of the AD process.

The analysis will focus on four specific markets as representative cases. The impact of inorganic fertilizer on biofertilizer, including the infrastructure has been examined. This will involve calculating the percentage change in emissions of biofertilizer versus synthetic fertilizer across all impact categories. To facilitate the comparison of the impacts between synthetic fertilizers and the obtained biofertilizers, Table 2 is presented, detailing the composition of nitrogen, phosphorus, and potassium of the different obtained biofertilizers from digestate.

Table 2 NPK composition of the different biofertilizers produced and their type

	N	P	K	Type
	%			
A	15	1	3	15–1–3
B	2	0	3	2–0–3
C	2	0	3	2–0–3
D	7	0	3	7–0–3
E	6	0	3	6–0–3
F	7	0	3	7–0–3
G	9	0	3	9–0–3
H	2	0	3	2–0–3
I	7	0	3	7–0–3
J	6	0	3	6–0–3
K	7	0	3	7–0–3
L	6	0	3	6–0–3
M	6	0	3	6–0–3
N	7	0	3	7–0–3
O	7	0	3	7–0–3
P	6	0	3	6–0–3
Q	2	0	3	2–0–3
R	6	0	3	6–0–3
S	2	0	3	2–0–3
T	6	0	3	6–0–3
U	2	0	3	2–0–3
V	2	0	3	2–0–3
W	6	0	3	6–0–3

Analysis of results by market type

Market A This case represents the phenomenon of infrastructure oversizing observed in the analysis by impact categories, as well as being one of the markets that are not self-sufficient in the anaerobic digestion process. The significant impact increase is evident in ADP (560%) and in three ecotoxicity categories, mainly related to infrastructure impacts. This increase reflects the consequences of not being self-sufficient and using non-renewable energy for operation, as evidenced by the 99% increase in ADP-FF and the 213% increase in GWP 100. In the case of market A, due to the composition of the biofertilizer, it has been compared with a 15:1:3 (N:P:K) mineral fertilizer. Overall, it can be seen the great impact of this oversizing since Fig. 5. shows that the commercial fertilizer outperforms the biofertilizer in all impact categories of the CML-IA method, concluding that biofertilizer is, in this case, less sustainable than a common synthetic fertilizer.

Market D This market again has a much larger infrastructure than necessary, although, in this case, the volume of waste it gets is sufficient to generate the heat required by the digester, so it does not require energy from the electricity grid. Again, the oversizing is represented by a biofertilizer that has twice the abiotic depletion impact as the inorganic fertilizer. In this case it has been compared with a 7:0:3 (N:P:K) mineral fertilizer. By being self-sufficient, the results obtained in the remaining impact categories are considerably improved (Fig. 5), resulting in a biofertilizer that is competitive in the categories of fossil fuel depletion and ozone layer destruction, as well as getting overall better results than the previously analyzed market A.

Market G This case is the standard case, as it represents the remaining 19 markets in that it does not present problems of oversizing or self-sufficiency, as well as using varied organic waste at the origin of the produc-

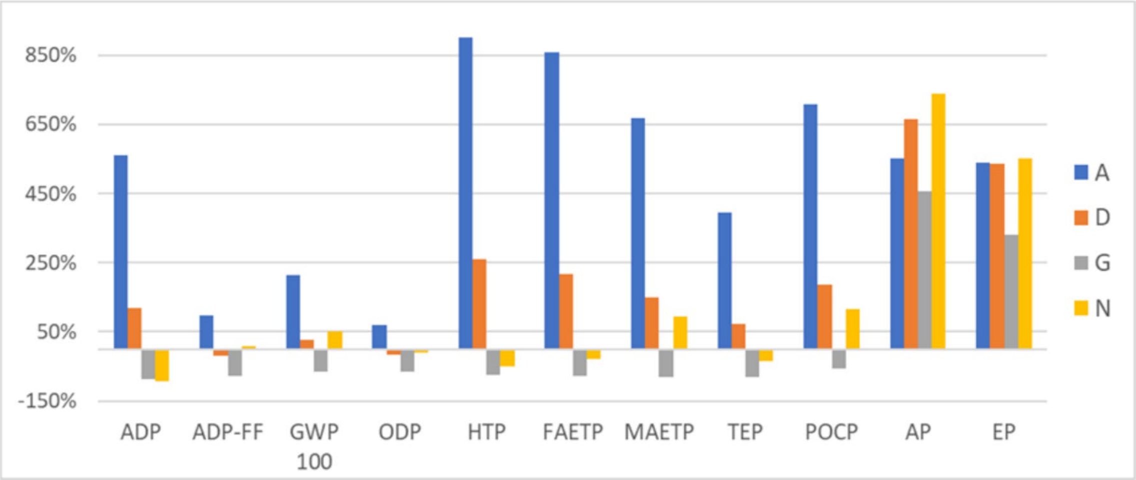


Fig. 5 Percentage variation in environmental impact between biofertilizer and synthetic fertilizer in selected markets

tion process. This is the best possible case, as it reproduces the real conditions of a digestate biofertilizer coming from an AD plant correctly dimensioned for the incoming volume of waste, thus allowing comparison on equal terms with the inorganic fertilizer. Biofertilizer from market G has been compared with a 9:0:3 (N:P:K) mineral fertilizer. In Fig. 5, it is illustrated that biofertilizer leads to emissions savings in 9 out of the 11 evaluated categories, improving upon the results of synthetic fertilizer. The emissions savings in these 9 categories range from 86% for ADP to 55% for POCP. The most significant reductions were seen in the ADP category, followed by the 4 categories of ecotoxicities, with savings ranging from 81 to 76%. This is because producing fertilizer from organic waste eliminates the need to use natural resources to obtain nutrients, such as potassium, nitrogen, or phosphorus. In addition, the self-sufficiency of the AD process and its lack of impact from fossil fuels used in the national electric mix (especially the absence of coal-produced electricity) significantly reduce GWP by 64% and ADP-FF by 77%. It is important to highlight that none of the 23 markets present an impact reduction in the categories of acidification and eutrophication. This phenomenon is mainly linked to the ammonia emissions that occur during the composting process and do not suffer any control or filtering before being directly emitted into the atmosphere. The nitrogen in this ammonia is directly responsible for the lack of environmental competitivity in these categories.

Market N Market N and Market E present the opposite case to Market A: an under-sizing of the infrastructure. Although Market N generates a high volume of waste, the anaerobic digester is undersized relative to this influx. As a result, not all the waste can be efficiently processed, leading to insufficient biogas generation to meet the plant's energy needs. A priori, this under-sizing should improve the results concerning the typical case (as seen in the large natural resource depletion result, with an impact reduction of 92%), as the impact of the infrastructure per kg of biofertilizer is considerably reduced. However, the energy required from the grid means adding the impacts of the national energy mix, increasing the results for all categories. For this reason, the N market shows emission savings in 5 of the impact categories assessed, as shown in Fig. 5. Biofertilizer from market N has been compared with a 7:0:3 (N:P:K) mineral fertilizer.

The dependence on the national grid for digestate production is readily appreciated in the fossil fuel depletion and global warming categories where, despite the offset produced by the great under-sizing of the infrastructure, the biofertilizer has more significant impacts than the respective inorganic fertilizer.

It is important to note that the biofertilizers assessed in this study may offer additional agronomic benefits beyond their NPK composition. These include organic carbon, which can enhance soil structure and water retention, and various micronutrients (e.g., calcium, magnesium, sulfur, iron) that contribute to improved plant health. However, such benefits were not included in the present LCA, as post-application impacts were excluded from the system boundaries. As a result, these contributions are not reflected in the comparison with inorganic fertilizers.

In addition, the organic carbon content in the biofertilizer could contribute to carbon storage in agricultural soils. This potential sequestration effect is influenced by factors, such as soil type, climate, and application practices. However, the present study did not account for these benefits, as post-application impacts were excluded from the LCA system boundaries. As such, the environmental advantages associated with soil carbon retention are not reflected in the current results. Future research should address this dynamic to better assess the full climate mitigation potential of digestate-based fertilizers.

Unit comparison between fertilizer and biofertilizer for the 23 markets

Throughout the study, the construction of the biofertilizer production model has been detailed, and its environmental evaluation has been compared to the current alternative: inorganic fertilizers. For this purpose, inorganic fertilizers of the same composition as the biofertilizer obtained for each of the 23 markets studied through anaerobic digestion and standardized compost have been chosen.

The comparison results vary depending on the amount and type of waste in each case and the environmental category being considered. To enable an integrated comparison across the 23 food markets evaluated in this study, an aggregated environmental score was calculated for each case using the optional steps of normalization, weighting, and aggregation in the Life Cycle Impact Assessment. In the normalization phase, each impact category result was divided by its respective reference value, making the results dimensionless and allowing them to be compared across categories. The normalization factors applied were those of the CML-IA baseline v3.07/EU25 method, as implemented in SimaPro 9.5.0, ensuring alignment with the European context of the study. Next, weighting was applied by multiplying the normalized impacts by their respective environmental relevance factors from the same method. Finally, the weighted scores were aggregated into a single indicator per market—referred to here as the aggregated score—which allows for a comprehensive comparison of environmental performance

Fig. 6 Unitary comparison between the biofertilizer and the organic fertilizer across all markets

among the different market scenarios. These aggregated scores form the basis for the comparative results shown in Fig. 6. The relative environmental impact savings of biofertilizers compared to inorganic fertilizers of the same composition are illustrated in Fig. 6. As can be seen from the figure, 17 out of the 23 markets evaluated demonstrate emission reductions across 11 impact categories, with an average saving of 55%.

Considering the results shown in Fig. 6, 75% of the studied markets (17 out of 23) led to a reduction of the total environmental impacts of their comparator fertilizer. The following cases stand out negatively: Market A, due to the oversizing of the equipment, which impacts infrastructure sizing and the process' energy demand from the grid. Due to the oversizing of the infrastructure, market D is better than Market A as the process is self-sufficient. Due to the under-sizing of the infrastructure regarding the volume of waste treated, Markets N and E make the process dependent on electricity from the grid. And markets H and S, whose waste mixture contains only vegetables, due to slight infrastructure oversizing.

In the remaining 17 cases, an average saving of 55% of the impacts of conventional fertilizer is obtained, thus demonstrating that biofertilizer is a more sustainable alternative for providing nutrients to soils in agriculture, as well as being an effective method of recovering a by-product (digestate) of an AD process that already recovers waste from various food markets.

Although the study includes a structural sensitivity analysis regarding the influence of infrastructure-related emissions (as shown in Fig. 3c), it does not incorporate a formal quantitative uncertainty assessment. The use of a standardized infrastructure model across all markets—while ensuring methodological consistency—relies on assumptions, such as uniform plant lifetime, size, and efficiency. These simplifications may influence the results in scenarios with significant under- or overutilization of infrastructure. Future research should include uncertainty modeling based on variable infrastructure lifetimes, capacities, and operational conditions, in order to provide a more robust characterization of the environmental performance under realistic variability.

Conclusions

This study compared the environmental impacts of biofertilizers derived from digestate with conventional mineral fertilizers across 23 markets. In 19 of these markets, where anaerobic digestion plants are adequately sized and biogas production allows for energy self-sufficiency, environmental benefits were observed in all assessed impact categories except for acidification and eutrophication. In market G, representative of these self-sufficient markets, emission savings ranged from 55% for POCP to 86% for ADP. However, AP and EP categories showed significant increases in emissions, ranging from 331.2% to 455.2%, respectively. When the infrastructure impact of the anaerobic digestion plant was excluded, results improved in all impact categories except for AP and EP, where the variations were minimal.

In contrast, the remaining four markets showed lower environmental benefits. Biogas production was insufficient for energy self-sufficiency, and the infrastructure was undersized in the two largest markets (E and N), which handle larger waste volumes and have higher energy demands. In these cases, biofertilizer benefits were reflected in only five impact categories. In the two oversized markets, environmental benefits were even lower. In market D, where energy self-sufficiency was achieved, benefits were observed only in the categories

ADP-FF and ODP. In market A, where self-sufficiency was not reached, and only fish waste was treated, no benefits were recorded in any impact categories. These four markets, excluding infrastructure impacts, showed slight improvements in the larger markets. In contrast, significant improvements were observed in the oversized markets (A and D), reaching emission savings in all categories except acidification and eutrophication, with savings exceeding 95% in some categories.

The high impacts of biofertilizers in the acidification and eutrophication categories are mainly due to NH_3 emissions during the composting process, which significantly contributes to soil acidification and eutrophication of nearby aquatic ecosystems, affecting environmental quality.

Overall, biofertilizers generated environmental benefits in 19 of the evaluated markets, representing a sustainable alternative for agricultural soil use. However, the study highlights the importance of proper infrastructure sizing and efficient biogas production to maximize environmental benefits.

To compare across the 23 evaluated markets, the scores for each impact category were normalized to unit values, allowing for the calculation of an aggregate total score for each market. The findings indicate that in 17 of the 23 assessed markets, emissions reductions were observed across the 11 impact categories, with an average reduction of 55% compared to mineral fertilizers.

In addition, the study confirms that waste composition influences biogas yield and biofertilizer quality, especially in cases where a predominance of low-energy substrates (e.g., vegetables) or single waste types resulted in reduced environmental performance. This reinforces the relevance of considering substrate profiles in future environmental assessments and system design.

Future research will focus on adjusting the size of anaerobic digestion facilities to match the actual volume of waste to be treated and optimizing the waste mix in each market to maximize energy self-sufficiency and enhance biofertilizers as an environmentally sustainable solution.

Abbreviations

AD	Anaerobic digestion
ADP	Abiotic depletion potential
ADP-FF	Abiotic depletion potential fossil fuels
AP	Acidification potential
EP	Eutrophication potential
F	Fish residue
FAETP:	Freshwater aquatic ecotoxicity potential
GWP	Global Warming Potential
GWP	100 Global Warming Potential
HTP	Human toxicity potential
LCA	Life Cycle Assesment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
M	Meat residue
MAETP	Marine aquatic ecotoxicity potential
ODP	Ozone depletion potential
PCOP	Photochemical oxidation potential
TEPT	Terrestrial ecotoxicity potential
TOC	Total Organic Carbon
V	Vegetables and fruits residue

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Author contributions
Carmen Martín-Sanz Garrido: conceptualization, methodology, investigation, writing—original draft, and formal analysis; Marta Revuelta-Aramburu: conceptualization, investigation, writing—original draft, writing—review and editing, formal analysis, supervision, and validation; Carlos Morales-Polo: conceptualization, investigation, writing—original draft, writing—review and editing, formal analysis, supervision, and validation; Ana María Santos-Montes: investigation, writing—review and editing, supervision, and validation.

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During the preparation of this work the author(s) used ChatGPT in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Competing interests
The authors declare no competing interests.

Author details
[1]ICAI School of Engineering, Comillas Pontifical University, Madrid, Spain. [2]Rafael Mariño Chair for New Energy Technologies, Comillas Pontifical University, Madrid, Spain. [3]Institute for Research in Technology (IIT), ICAI School of Engineering, Comillas Pontifical University, Madrid, Spain.

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