Life Cycle Assessment of the Production of Biofertilizers from Agricultural Waste

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Review

Life Cycle Assessment of the Production of Biofertilizers from Agricultural Waste

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Abstract: This study reviewed 98 references on the Life Cycle Assessment (LCA) of the conversion of agricultural waste into biofertilizers. Feedstocks were manure (39%), organic/food/wood waste (30%), and crop waste (26%). Biofertilizers were digestate, compost, biochar, and pellets, and full-scale application was prevalent. Approximately 64% of references cited anaerobic digestion (AD) and composting, often combined. Thermochemical and mechanical processes were less (24%) involved, mostly incineration and gasification (10% each) and pyrolysis (4%), with few cases of pelletization. Approximately 30% of references coupled LCA with an economic analysis tool. All references considered the Life Cycle Impact Assessment (LCIA) categories Global Warming Potential (GWP), Ozone Depletion Potential, Eutrophication, and Acidification. In overall AD, compared to other technologies, displayed the largest average impacts, particularly when the chosen functional unit (FU) involved manure. Composting provided lower average impacts compared to AD, and FU referring to organic/food waste largely topped manure. Thermochemical processes exhibited the smallest average impacts, compared to AD and composting, particularly when the FU was related to food/organic waste. In conclusion, further research is needed to explore technologies (particularly thermochemical and mechanical) applied at full-scale in different contexts and to the assessment of economic and social sustainability, identified as main knowledge gaps.

Keywords: agricultural; biochar; compost; digestate; fertilizer; waste

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1. Introduction

Agricultural systems have been necessary to provide human and animal food since prehistory. At present, we urgently require the transition to sustainable food production considering the whole value chain, according to the European regulations and policies, such as the Farm to Fork Strategy [1]. The application of the circular economy into agricultural systems will contribute to making Europe the first carbon-neutral continent by 2050 [2]. Global efforts are needed to increase nutrient use efficiency [3] and decrease the environmental impacts associated with biodegradable waste management [4]. The conversion of biodegradable waste into fertilizers, biofuels, and energy sources is a beneficial approach for reducing the environmental impacts of agricultural systems [5]. Improved waste management practices could help to decrease overall greenhouse gas (GHG) emissions associated with agricultural systems. Agricultural waste can be converted into value-added products [6,7], biofertilizers [3,8], and bio-energy sources [9–11], e.g., biofuels, biogas, etc. Also, due to the non-renewable nature of primary nutrients, nutrient recovery from waste materials is urgently necessary in agricultural production [12]. The conversion of biodegradable waste into biofertilizers implies long-term environmental and socio-economic benefits [4,13].

Regulations and policy aspects play a significant role in the context of biofertilizers. This is especially relevant in the circular economy, where producing biofertilizers allows us to obtain valuable products from waste and reduces dependence on chemical fertilizers. In terms of agriculture and breeding, the main standards at European level are as follows:

- Council Directive 86/278/EEC of 12 June 1986 on the protection of the environment, particularly of soil, when sewage sludge is applied in agriculture;
- Council Directive 91/676/EEC of 12 December 1991 on the protection of natural water against pollution caused by nitrates deriving from agricultural sources;
- L 95/1 regulation (EU) 2017/625 of the European Parliament and of the Council of 15 March 2017 on official controls and other official activities performed to ensure the application of food and feed law, rules on animal health and welfare, plant health, and plant protection products;
- Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 on making available on the market of EU fertilizing products and amending Regulations (EC).

The above-mentioned European regulations deliver key concepts to the theme of the conversion of agricultural waste into biofertilizers, such as the definition of possible feedstocks (manure, vegetable biomass, animal by-products, sewage sludge, and organic fraction of municipal solid waste), digestate (agro-zootechnical or agro-industrial) and compost, the amount of nitrates acceptable in agricultural waters and soil, the classification of legalized and marketable fertilizers, the possible uses of digestate (agronomic and for energy recovery), and the fertilizing properties and content of biofertilizers that can be used to enrich soils.

Knowledge of the environmental impacts related to technologies and practices applied to agricultural waste management is crucial to design improvement strategies.

The Agricultural Research Service of the United States of America (USDA) patented a new technology to extract ammonia from livestock wastewater and recycle it as a fertilizer [14]. The Resource Conservation and Recovery Act (RCRA) regulates the disposal of agricultural waste and encourages the recycling and recovery of agricultural residues in the United States [14]. In Canada, the Fertilizer Regulation [15] outlines the rules and specifications for fertilizers. The Department of Agriculture Cooperation of the Government of India has been responsible for administering the Fertilizer Control Order since 1985, establishing product-specific requirements, fertilizer sampling, and analysis techniques, and which compounds are suitable for soil biofertilizers [16].

The environmental impacts of the conversion of agricultural waste into biofertilizers have been previously assessed through Life Cycle Assessment (LCA) [17]. Biofertilizers deriving from agricultural waste provide an environmentally friendly alternative to mineral fertilizers, with lower impacts in all Life Cycle Impact Assessment (LCIA) categories [18]. In the recent past (i.e., from 2018 to 2024), nearly 100 scientific papers were published on the topic. Existing literature involves LCA applied to the conversion of agricultural waste into biofertilizers through composting [5], anaerobic digestion [19], and thermochemical processes [20]. Most are research studies, and just few are review studies providing an overview on feedstocks and technologies [12] and the conversion of biodegradable waste (including agricultural waste) into value-added products and energy [5] or have specific interest for poultry waste and biological and thermochemical processes [19] and for manure and thermochemical processes [20,21].

To the best of our knowledge, a review study specifically dedicated to exploring the potential of agricultural waste (instead of the wider category “biowaste”) as feedstock to produce biofertilizers and the related environmental impacts has not been published yet. This review analyzed LCA studies dedicated to the conversion of agricultural waste into biofertilizers, regulated in Europe by EU Regulation 1009/2019 [22]. The novelty of this review is to critically analyze the LCA studies describing biofertilizer production from agricultural waste published in the last 7 years (2018–2024), as the existing review studies involve a more general overview on biowaste and technologies or are, on the contrary, focused on specific feedstocks and processes. The main aim of this review was to deliver an updated and clear outline of the environmental impacts associated to the available technologies, of their maturity, and of the bottlenecks for the technology transfer to the industrial world, and to provide guidance in identifying perspectives to improve the environmental performances of the conversion of agricultural waste into biofertilizers at full-scale.

2. Materials and Methods

The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) method [23] was employed to systematically and rigorously select the articles analyzed in this scientific review. This method involves a four-phase process, ensuring that only the most relevant and high-quality studies are included: identification, screening, eligibility, and inclusion. This thorough selection process enhances the reliability and validity of the review's findings. The literature survey was performed on Scopus database by applying the keywords "LCA" and "fertilizer" and "composting" or "pelletization" or "granulation" or "anaerobic digestion" or "gasification" or "pyrolysis" or "combustion" in various combinations. The survey was carried out within the time frame from 2018 to 2024, including research articles and review papers published in English. After pre-selection based on titles and keywords, a further screening of the references was based on the abstract to ensure that the topic of the study was aligned with the objectives of this review. Then, the selected references were categorized according to type (research article or review), LCA features (methodology, functional unit, system boundaries), eventual combination of LCA with economic analysis tools, characteristics of farm/plant (context, scale, and location), applied technology (anaerobic digestion, composting, thermochemical, or physical–mechanical processes), technological maturity (lab, pilot, or full-scale), and characteristics of the output (type of biofertilizer and eventual other products). Finally, the LCA results reported in the selected references were critically analyzed, describing and quantifying the diverse impact categories reported in the studies.

3. Results and Discussion

3.1. Overview

According to the described methodology (Figure 1), 98 references (93 research articles and 5 review papers) were selected. The full list of 98 references, categorized as described in the Methodology, is in the Supplementary Materials.

The publishing trend from 2018 to 2024 is clear (Figure 2): every year, up to 24 scientific articles were published, with only 1–2 review papers. Due to the low number of review papers recently published on the production of biofertilizers from agricultural waste, a critical review of the existing literature on the topic is still missing; this represents the novelty of this study.

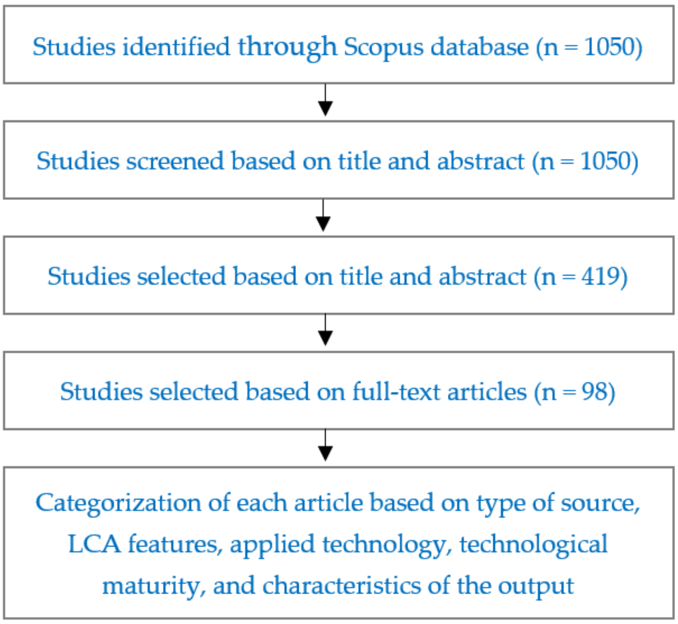

Figure 1. Description of the methodology applied for case study selection.

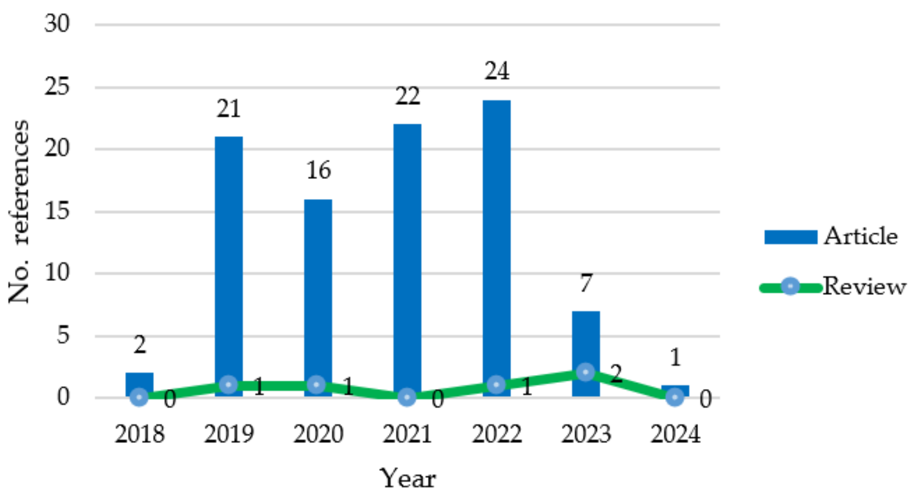

Figure 2. Classification of the selected references into scientific articles and review papers.

3.2. Feedstocks and Geographical Context of the Studies

The selected references involved different feedstocks: pig/cow/chicken manure (39%), wood and organic/food waste (typically the organic fraction of municipal solid waste) (30%), crop waste (26%, e.g., from maize, rice, grass, vines, and olives), and other types of waste (5%). Regarding the geographical context (Figure 3), Italy hosted 12% of the case studies, China 9%, the United States of America 8%, and Brazil 6%. Very few studies (1–2 each) were located in Asia, Australia, Europe, and Middle Eastern countries, while the context was not specified in 17% of the references. Existing literature is mostly interested into manure, while crop waste—highly heterogenous—needs more research to achieve consistency in the presented findings. As the results of LCA are largely affected by the local context [24], more studies referring to the same feedstock considered in different contexts (defined by the country and the available technologies, infrastructures, and population density) are necessary.

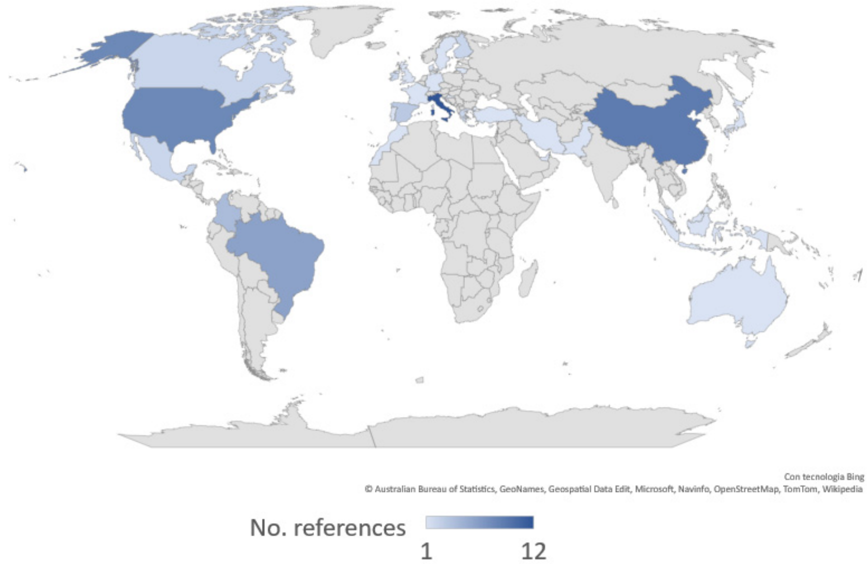

Figure 3. Localization of the case studies analyzed in the selected references.

3.3. Biofertilizers and Technologies

The obtained biofertilizers were digestate (24%), compost (21%), biochar (4%), and pellets (2%), with further production of biogas and syngas in 31% of the selected references. Other products (18%) were identified by the authors as "fertilizer", such as ammonium sulfate [6], hydrolyzed chicken feather waste [9], and ammonium bicarbonate from digestate distillation [9,25].

A thorough analysis was conducted on the applied technologies, displayed in a Pareto chart (Figure 4), where anaerobic digestion (37% of references) and composting (27%) were applied as single technologies or combined in sequence. The major contribution of anaerobic digestion and composting is clearly visible. Thermochemical processes (20% overall), as pyrolysis (8%), gasification (6%), and incineration (5%), were also considered. Few studies (4%) involved mechanical processes (primarily pelletization), applied directly to crop waste as cornstalks [3] or to the digestate obtained from the anaerobic digestion of organic waste [7,26–28]. Other technologies were also considered (12%), for example, transesterification [5], in which Jatropha seeds are used to produce biodiesel and the residual waste seeds as fertilizer, and combined anaerobic digestion and ammonia stripping [6] applied to a mix of orange waste and sewage sludge to obtain ammonium sulfate.

Regarding the technological maturity of the technologies implemented in the selected references, the full scale was predominant (85% of references) (Figure 5), while just 1 or 2 references per year considered the laboratory and pilot scale, and few studies (3%) did not provide any detail about the scale of the applied technology. For example, a study referred to a full-scale composting plant in Greece fed with the organic fraction of municipal solid waste and garden residues [3], along with another study on another pilot-scale anaerobic digestion plant in Pakistan fed with cow manure and potato crop residues [4]. Experiments describing the implementation of different thermo-chemical treatments, as slow and fast pyrolysis, gasification, and hydrothermal carbonization, were reported as referring to a plant fed with poultry litter [29].

Overall, the existing literature chiefly involved LCA studies considering biofertilizers deriving from biological processes applied at the full scale, often with a contextual production of energy. This provided good reference for the technological transfer to the industrial world; however, more studies exploring the application of thermochemical and mechanical processes at the full scale are necessary to provide a complete overview.

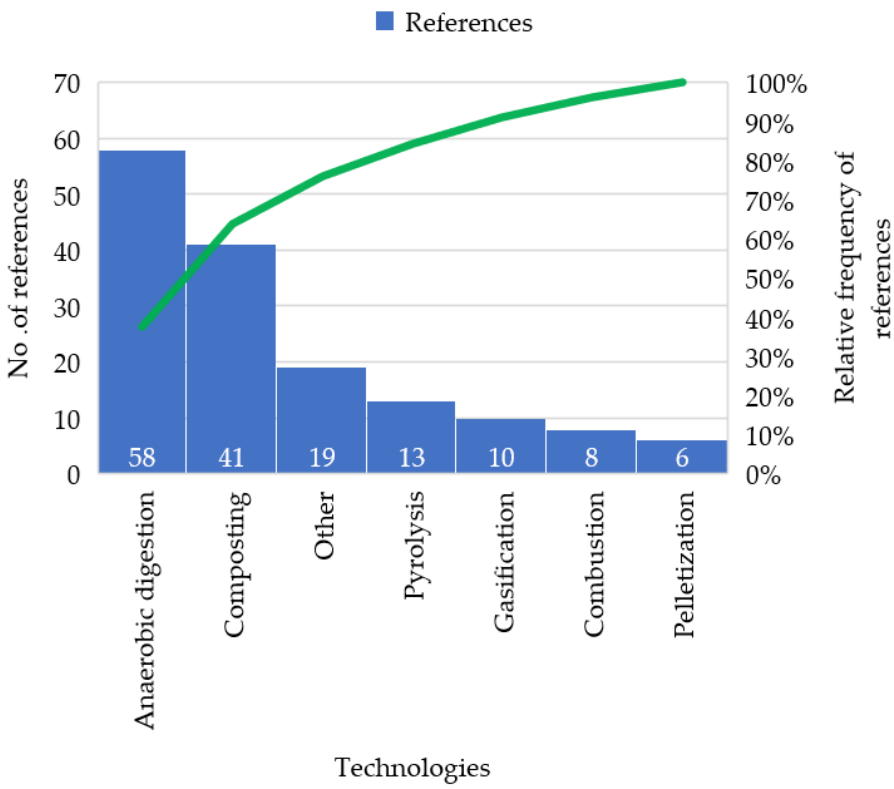

Figure 4. Categorization of the technologies applied in the selected references. The green line displays the relative frequency of the selected references.

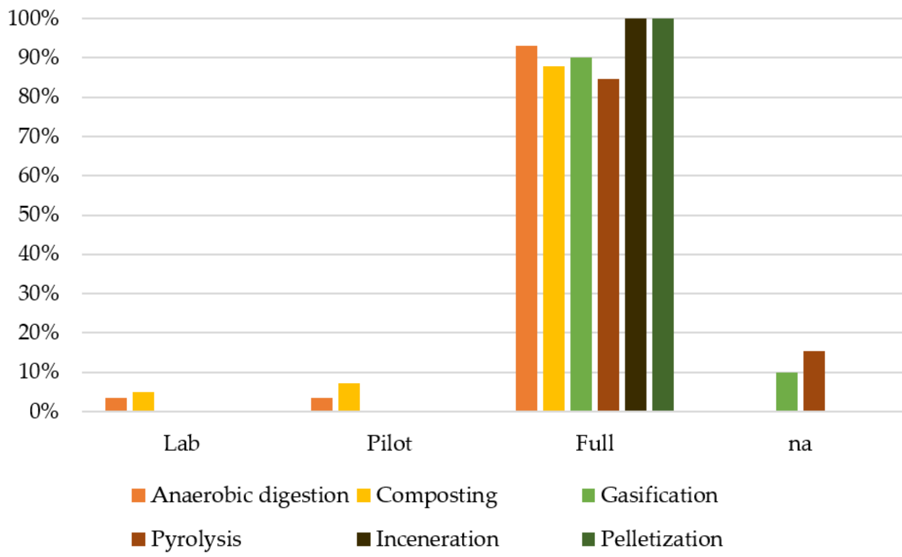

Figure 5. Details about the scale of the technologies applied in the selected references (na: not available).

The average EU-27 waste management rate for large-scale operations is 31% for material recycling, 18% for anaerobic digestion and composting, 27% for energy recovery and incineration, and 23% for landfilling [30]. With 30% of materials recycled, 26% of waste are disposed into composting and anaerobic digestion, 21% to energy recovery and incineration, and 21% to landfills, and Italy's performance on waste management is aligned with the average European trend [30]. In several EU-27 countries, including Italy, the plants implementing the thermochemical treatments are fewer compared to other technologies due to regulatory, social, and financial barriers. This happens as the EU regulations imply long procedures for the authorization of new installations, and social acceptance is often scarce [31]. The financial feasibility of the plant depends on the plant's capacity and other factors such as the cost of energy, nutrient recovery, product market value, and technology flexibility [32].

3.4. Life Cycle Assessment Features

Within the selected references, LCA was mostly (69% of references) applied as single assessment methodology (Figure 6) or in combination with a preliminary economic analysis (15%), techno-economic analysis (TEA) (9%), or Life Cycle Costing (LCC) (6%), and in one single case, in combination with Water Footprint (WF). Overall, less than one-third of the selected references included an economic analysis of the applied technology in varying degrees of detail, from a preliminary evaluation of the operational costs [33,34] to a complete analysis involving the capital costs [24,35,36]. There are numerous economic assessment tools available, such as techno-economic analysis (TEA) [10,37] and Life Cycle Costing (LCC) [11,38]. Based on the results of this literature review, the studies applying LCA combined with economic analysis can provide interesting results and guide further research. For example, LCC was applied to a case study in Italy [11], hypothesizing seagrass valorization via anaerobic digestion or composting as alternatives, and composting was found the most convenient from an economic point of view. On the contrary, for the same case study, LCA revealed that anaerobic digestion has the most positive impact on the environment. In another study [12], coupling anaerobic and aerobic processes (e.g., conversion of the digestate into compost) led to the valorization of pruning and dairy residues and manure. Another interesting study [39] showed the importance of achieving GHG neutrality through the installation of solar panels on farms of both large and small sizes. Techno-economic and environmental impact assessments applied on a case study in USA [40] showed the conversion of manure into biochar in the field through a portable biorefinery unit.

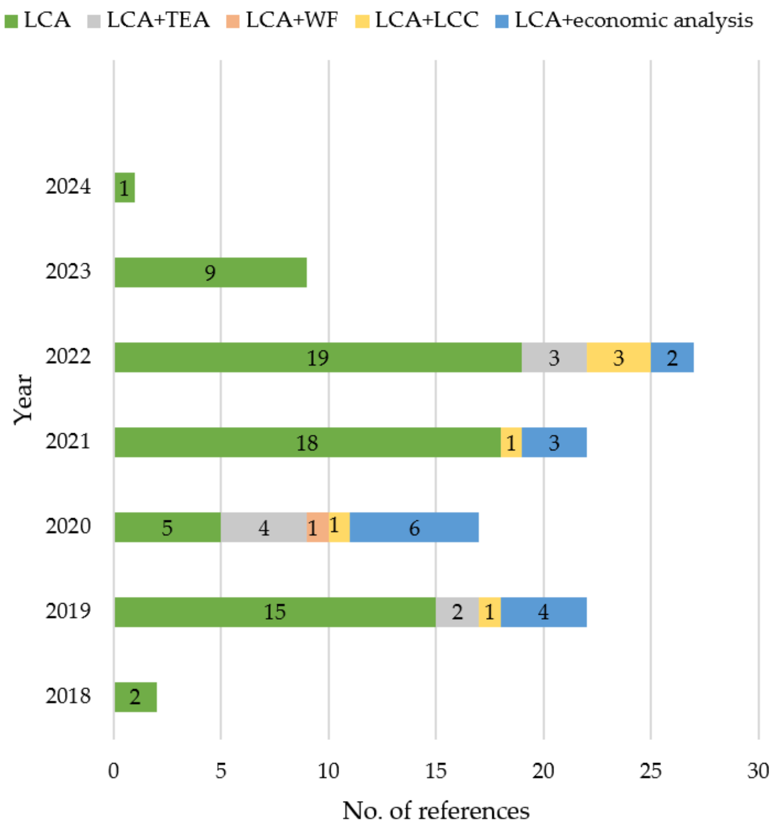

Figure 6. Assessment tools applied in the selected references (Life Cycle Assessment—LCA, Life Cycle Costing—LCC, techno-economic analysis—TEA, Water Footprint—WF).

Moreover, social and policy/regulatory aspects are crucial for a comprehensive analysis of the feasibility of a proposed technology in any specific context [36]. The combination of LCA with other assessment tools, particularly the ones involving economic and social impacts, can provide a useful overview of "non strictly technological" issues related to biofertilizers production from agricultural waste. This is, in our opinion, a knowledge gap, and more research based on LCA combined with other methodologies is needed.

Other significant issues that may guide future research are as follows. The methodological dissimilarities in the Life Cycle Assessment (LCA) studies selected in this review study make difficult to identify the most significant impacts through comparison. ISO 14040 [41] clarifies that comparable research conditions and hypotheses are necessary to compare LCA surveys. Also, the context in which any case study was evaluated is crucial, as significant differences in the results of an LCA were found when applying the same analysis in countries characterized by diverse energy mixes [42].

Technological development needs to be supported by the current infrastructure, feedstock supply chains, market opportunities, socio-economic issues, and political contexts [43,44].

The selected references considered different system boundaries (Figure 7): cradle-to-gate approach was frequent (54% of references), followed by cradle-to-grave (38%) and cradle-to-cradle (2%). In 6% of the references, system boundaries were not identified. The cradle-to-gate approach measures the environmental impacts up to the point where the product leaves the factory gate, overlooking the impacts of consumer use and end-of-life operations. As it is difficult to retrieve data about the use and end-of-life phases, this is, probably, the reason why cradle-to-gate is the most common system boundary applied in literature.

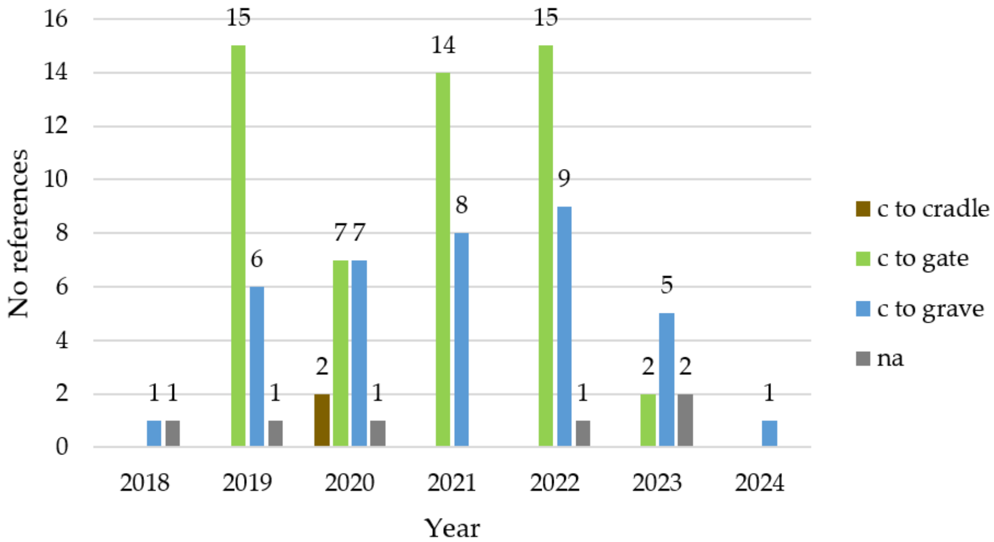

Figure 7. Life Cycle Assessment system boundaries applied in the selected references.

Another important aspect of LCA is the functional unit (FU), as it provides the reference for the computation of all inputs and outputs of the system [2]. In the selected studies, FUs refer to the input (52% of references) or output of the applied technology (35%), showing a wide range of feedstocks and products, while in 13% of studies, the FU was not specified. FUs were in the selected references as follows: food, crop waste and organic fraction of municipal solid waste (31%), manure (15%), electricity or heat (14%), biofuel (7%), compost and biofertilizers (6%), digestate (2%), biochar (2%), and other minor categories (10%). Overall, even if the existing literature usually clearly specifies the FU, a gap in the clarity of the data was also found. As the FU is crucial for analyzing and reporting the results of different LCA studies, future research should always report the FU and choose it to be consistent with the existing literature for reference to provide a robust dataset for the transfer to the industrial world.

3.5. Life Cycle Impact Assessment Results

Approximately 81% of the selected references detailed impact categories (the most common were Global Warming Potential, Eutrophication, Acidification, Ozone Depletion Potential, Terrestrial and Freshwater ecotoxicity, Mineral Resource Scarcity, Land Occupation, Human Toxicity, and Water Depletion) considered in the Life Cycle Impact Assessment (LCIA) according to the ReCiPe model [45]. However, not all selected references considered the same impact categories, and some studies did not declare the specific LCIA categories accounted. The impact categories predominantly reported (70% of selected references) were Global Warming Potential, Eutrophication, Acidification, and Ozone Depletion Potential. Therefore, only references presenting the LCIA results based on these four impact categories were included in the presented discussion. The selected LCIA results were classified according to different criteria. The first criterion was the applied technology, e.g., anaerobic digestion, composting, thermochemical processes, and pelletization. Within each of the four technology categories, the second categorization criterion applied was the chosen FU, which involved the input, e.g., manure or organic/food waste, or the output of the process, e.g., amount of electricity or heat generated or biofuel or biochar produced.

Considering the LCIA results, the selected references provided positive and negative values, e.g., produced and avoided emissions for each of the four impact categories. However, overall, the four considered technologies applied to the production of biofertilizers from agricultural waste implied positive emissions on average. When anaerobic digestion occurred (Figure 8), compared to other FUs, manure was associated with the largest impacts across all four impact categories (+85% Global Warming Potential). The average values of 1.7×10^3 kg CO_{2eq} for Global Warming Potential, 8.6×10^2 kg CFC for Ozone Depletion, 2.8×10^1 kg PO_4 for Eutrophication, and 8.4×10^1 kg SO_2 for the Acidification Potential were reported in detail. When the amount of electricity or heat was chosen as FU, avoided emissions (−133% compared to manure) were observed for Eutrophication. Unfortunately, the studies considering FU related to biofuel provided very few LCIA results, and no statistical analysis was possible. The anaerobic digestion of food/organic waste provided, on average, avoided impacts for Terrestrial Ecotoxicity (in average −0.4 kg DCB) and Ozone Depletion (in average -2.8×10^{-5} kg CFC).

The second most applied technology in the selected studies is composting (Figure 9). Overall, for all considered impact categories, the highest impacts were associated with FUs related to food/organic waste. Compared to anaerobic digestion, the impacts reported by the studies considering FUs related to manure were lower overall (−90%). The Global Warming Potential observed for composting manure was −88% compared to anaerobic digestion, with the same trend seen for the impact categories Eutrophication (−93%) and Acidification (−89%). Regarding Ozone Depletion, the available data were ascribed to FUs related to food/organic waste, with an average value equal to 4.3×10^{-2} kg CFC.

Regarding thermochemical processes, the available LCIA results are associated with FUs involving food/organic waste (43%) and manure (35%), as well as based on produced electricity/heat and biofuel (22%) in less references to FUs. From the available data, the impacts were related to incineration (43% of references), gasification process (39%), and pyrolysis (18%). The greatest impacts (Figure 10) for all LCIA categories were associated with FUs related to food/organic waste compared to manure. Regarding the referenced applying FUs related to electricity/heat and biofuel, the reported data were not sufficient to allow for any statistical analysis.

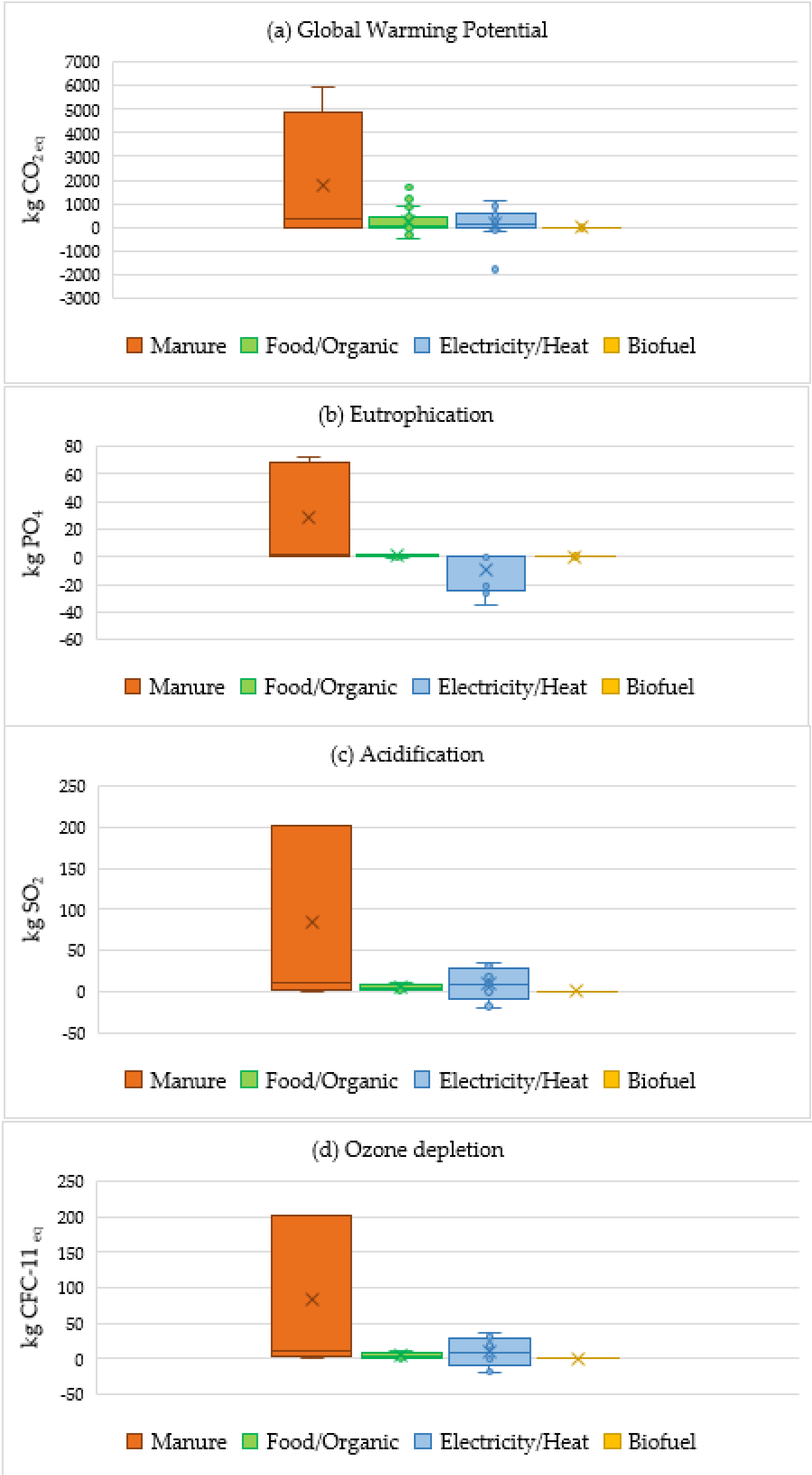

Figure 8. Results of Life Cycle Impact Assessment presented in references involving anaerobic digestion: (**a**) Global Warming Potential, (**b**) Eutrophication, (**c**) Acidification, (**d**) Ozone Depletion (the median value for each series is represented by the line and the average value by "×", and the bars show the value at the lowest and highest points).

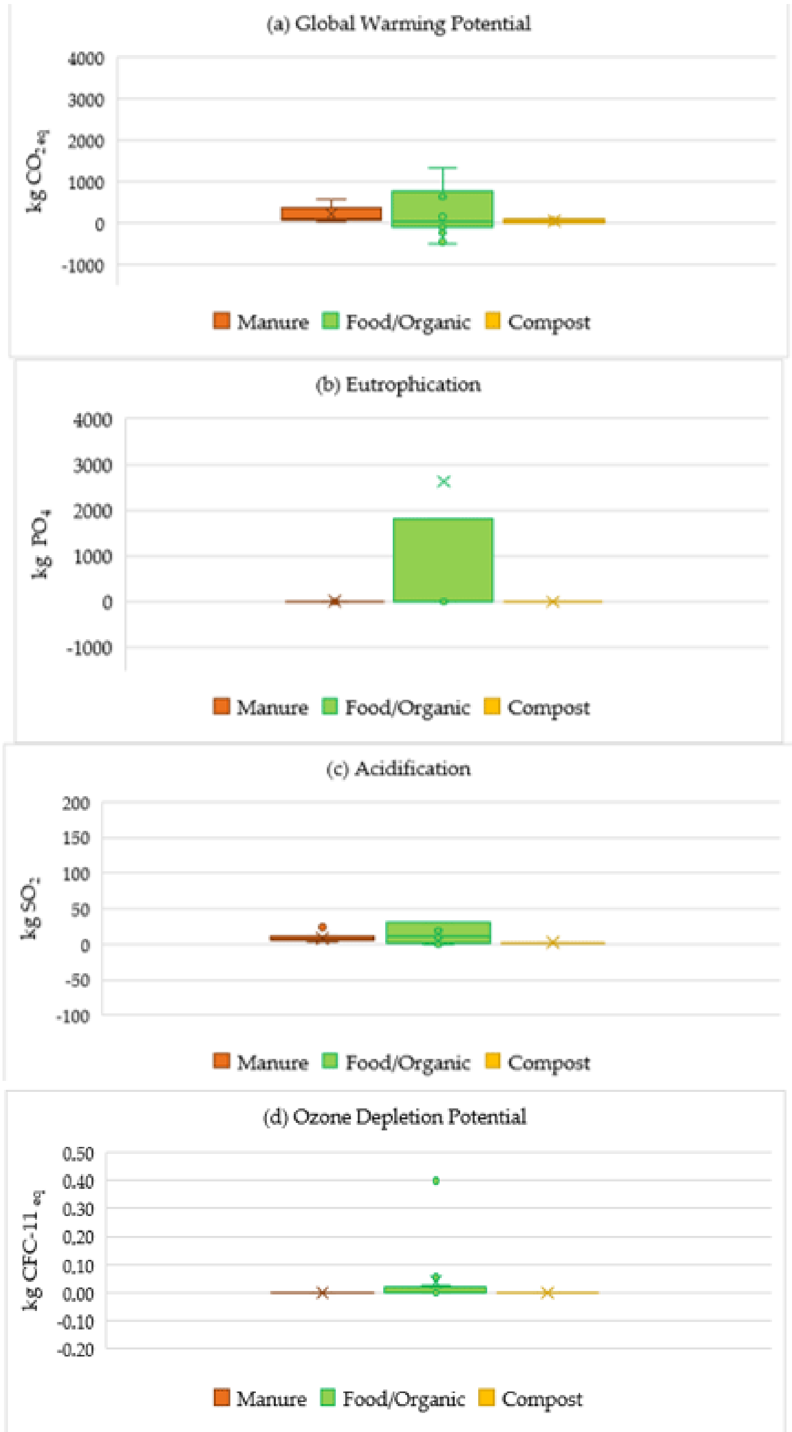

Figure 9. Results of Life Cycle Impact Assessment presented in studies involving composting: (**a**) Global Warming Potential, (**b**) Eutrophication, (**c**) Acidification e (**d**) Ozone Depletion (the median value for each series is represented by the line and the average value by "×", and the bars show the value at the lowest and highest points).

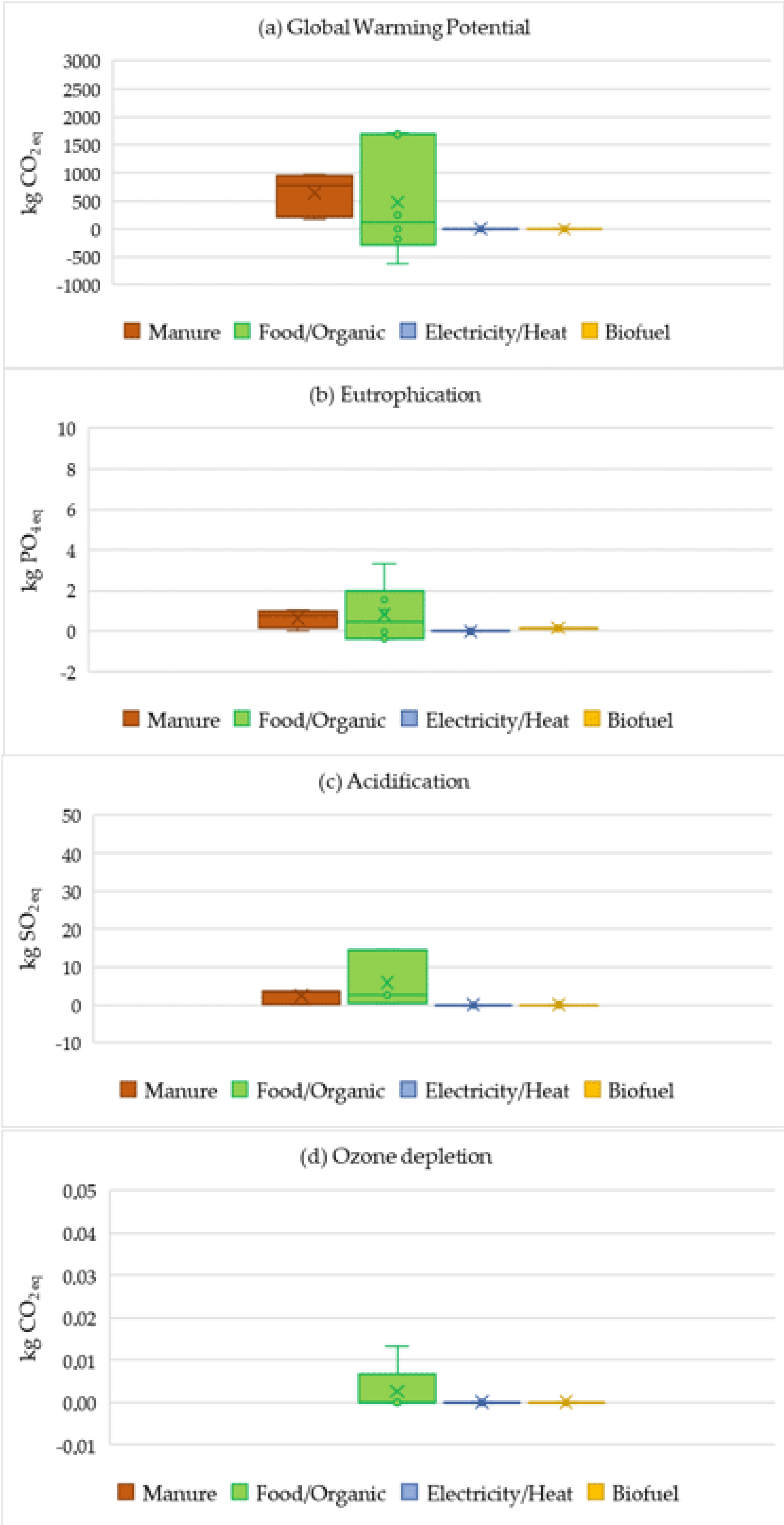

Figure 10. Result of interpretation of impact categories within the LCA analysis for thermochemical treatments: (**a**) Global Warming Potential; (**b**) Eutrophication; (**c**) Acidification; and (**d**) Ozone Depletion (the median value for each series is represented by the line and the average value by "×", and the bars show the value at the lowest and highest points).

The reviewed references also reported LCIA results associated with pelletization. The presented data only covered five case studies, making it difficult to conduct a proper statistical analysis of the impact values within the FU families. However, within the few available data, avoided impacts for Global Warming Potential for FUs related to food/organic waste (average value -1.4×10^1 kg CO_{2eq}) and electricity/heat (average value of -2.6×10^2 kg CO_{2eq}) were reported.

Comparing the applied technologies, anaerobic digestion exhibited the highest average impacts overall compared to composting and thermochemical processes. Considering the most studied feedstocks, manure produced higher impacts on average when fed via anaerobic digestion (1.7×10^3 kg CO_{2eq} for Global Warming Potential, 8.6×10^2 kg CFC for Ozone Depletion, 2.8×10^1 kg PO_4 for Eutrophication, and 8.4×10^1 kg SO_2) compared to food/organic waste (2.5×10^2 kg CO_{2eq} for Global Warming Potential, 4.5 kg CFC for Ozone Depletion, 0.6 kg PO_4 for Eutrophication, and 4.5×10^1 kg SO_2). The trend is opposite for the other technologies. Considering composting, food/organic waste produced higher impacts on average (6.3×10^2 kg CO_{2eq} for Global Warming Potential, 3.9×10^2 kg CFC for Ozone Depletion, 2.6×10^3 kg PO_4 for Eutrophication, and 1.9×10^1 kg SO_2) compared to manure (2.1×10^2 kg CO_{2eq} for Global Warming Potential, 3.5×10^{-5} kg CFC for Ozone Depletion, 2.0 kg PO_4 for Eutrophication, and 9.1 kg SO_2). Regarding thermochemical technologies, food/organic waste produced higher impacts on average (4.7×10^2 kg CO_{2eq} for Global Warming Potential, 2.6×10^{-3} kg CFC for Ozone Depletion, 8.4×10^{-1} kg PO_4 for Eutrophication, and 5.8 kg SO_2) compared to manure (6.5×10^2 kg CO_{2eq} for Global Warming Potential, 0.6 kg PO_4 for Eutrophication, 2.5 kg SO_2, and no data available for Ozone Depletion). Based on the mentioned LCIA results, it seems that the lowest environmental impacts could be ascribed to food/organic waste fed via thermochemical processes, followed by food/organic waste fed via anaerobic digestion and by manure fed via composting. On the other hand, the highest environmental impacts could be credited to manure fed via anaerobic digestion.

For a preliminary comparison, considering the few data available on the impacts associated with the pelletization of food/organic waste, the average Global Warming Potential (-1.4×10^1 kg CO_{2eq}) is an avoided impact compared to the positive impacts associated with anaerobic digestion, composting, and thermochemical processes applied to food/organic waste. Future research should improve the analysis of the environmental impacts associated with mechanical processes applied to agricultural waste to produce biofertilizers.

4. Conclusions

Within the selected 98 LCA studies exploring the production of biofertilizers from agricultural waste published between 2018 and 2024, the focus about feedstock was predominantly (69% of the references) on manure and wood/organic/food waste. Crop waste, considered in 26% of the studies, can be extremely diverse, and it needs more research to deliver consistent findings. Regarding the obtained biofertilizers, digestate, compost, and biochar were prevalent. The selected references describe principally mature technologies applied at the full scale, based on 64% of the studies on biological processes (anaerobic digestion or composting, often combined) and 24% on thermochemical processes (incineration, pyrolysis and gasification), while just a few explored mechanical processes such as pelletization. This provides good reference for the technological transfer to the industrial sector; however, more studies exploring the application of thermochemical and mechanical processes at the full scale are necessary to deliver a complete overview. LCA was mostly (69% of the references) adopted as single assessment methodology, occasionally (30%) in combination with an economic analysis tool, while none explored the social impacts.

The chosen system boundaries were generally cradle-to-gate, though the selected FUs were diverse and based on the feedstock or on the outputs of the applied technologies. Approximately 79% of selected references included four LCIA categories: Global Warming Potential (GWP), Ozone Depletion Potential, Eutrophication, and Acidification. Overall, the considered technologies (e.g., anaerobic digestion, composting, thermochemical processes, and pelletization) implied positive emissions on average, while the few data available for pelletization exhibited negative GWP (avoided emission). Comparing the applied technologies, thermochemical ones revealed the lowest impacts, particularly when food/organic waste was involved, compared to anaerobic digestion and composting. The highest impacts can be ascribed to anaerobic digestion, especially when the chosen FU concerned manure. Based on the LCIA results retrieved from this review, it seems that thermochemical technologies represent the best options—from the point of view of limiting the environmental impacts produced—for the conversion of food/organic waste and manure into biofertilizers. While considering the feedstocks most investigated by the existing literature, food/organic waste creates lower impacts if fed via thermochemical processes, followed by anaerobic digestion and composting. Regarding manure, the produced environmental impacts are lower for composting, followed by thermochemical processes and anaerobic digestion. In conclusion, as LCA results are largely affected by the local context, more studies referring to the same feedstock considered in different contexts (defined by country; by available technologies, infrastructures, and population density; and by social aspects) and adopting consistent FUs are necessary to provide reference. Moreover, the combination of LCA with other assessment tools, particularly the ones involving economic and social impacts, can offer a useful overview of "non strictly technological" issues, and the economic potential of technology greatly influences decision-making in the industrial world.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17020421/s1, Table S1: Full list of 98 references analyzed in the review paper.

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