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Review

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A Bibliometric Anatomy of Literature on Bio-Based Fertilisers with Insights into Environmental Impacts and Evaluation Approaches

Carlos Alberto Torres-Guerrero [1,*], Nancy Peña [1], Joan Colón [1], Daniel Egas [1,2], Ana Robles-Aguilar [1], Laia Llenas [1] and Jorge Senán-Salinas [1]

[1] BETA Tech Centre, University of Vic—Central University of Catalonia, Ctra. de Roda 70, 08500 Vic, Spain
[2] Mérieux NutriSciences—Blonk, Marten Meesweg 8, 3068 AV Rotterdam, The Netherlands
[*] Correspondence: carlosalberto.torres@uvic.cat; Tel.: +34-93-881-61-68 (ext. 8435)

Abstract

Bio-based fertilisers (BBFs) are gaining attention as sustainable alternatives to mineral fertilisers due to their potential for nutrient recovery, reduced environmental emissions, and improved soil health. However, their broader adoption is hindered by regulatory uncertainty, quality inconsistencies, and methodological variability in assessing their environmental impacts. This study can reveal about the body of research on bio-based fertilisers (BBFs), using a hybrid methodology that combines bibliometric and content analysis. A total of 247 publications from 2001 to 2024 were reviewed to identify research trends, environmental concerns, and assessment approaches. Results show a sharp increase in BBF-related publications after 2016, driven primarily by European and North American research, with growing focus on life cycle assessment (LCA) and nutrient recovery. The in-depth analysis of the ten most cited LCA and non-LCA studies highlights key methodological differences: non-LCA studies frequently rely on empirical fieldwork and generate primary data, whereas LCA studies typically synthesise secondary data to provide broader system-level insights. Despite this complementarity, the lack of methodological harmonisation poses a barrier to consistent comparison and interpretation. The findings highlight the need for a unified, standardised assessment framework to reliably evaluate the environmental performance of BBFs and support their effective implementation within circular and sustainable agricultural systems.

Keywords: sustainability; life-cycle-assessment; alternative fertilisers; nutrient recovery; circular economy; soil nutrients; in-depth analysis

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1. Introduction

Mineral fertilisers have played a critical role in supporting global food security and population growth for decades. Since 1960, their global consumption has increased drastically, driven by the cultivation of modern varieties and the adoption of intensive cropping systems [1]. The most recent estimation from 2019 reveals an overall consumption of 108 Mt of nitrogen (N), 42 Mt of phosphorus (P), and 35 Mt of potassium (K), with Asia experiencing the most significant growth [2]. However, fertiliser production remains heavily dependent on non-renewable resources. While the nitrogen in N-based fertilisers is sourced from atmospheric N_2, the Haber–Bosch process has historically depended on natural gas for both energy and hydrogen, leading to significant fossil fuel use. In contrast, P and K fertilisers rely on finite phosphorus and potassium rock reserves. This poses challenges for food safety and sustainability [3].

Throughout their lifecycle, from mining and manufacturing to field application, fertilisers contribute to environmental degradation when not managed properly [4,5]. They are major sources of soil, water, and air pollution [1], highlighting the need for global initiatives to promote sustainable alternatives towards a more circular and environmentally conscious agriculture.

Several countries have implemented policies for sustainable fertiliser management, including China's Zero Growth of Fertiliser Action [6], the USA's Agriculture Nutrient Management and Fertiliser Initiative [7], and the UK's Nutrient Management Plan [8]. At the European level, the European Commission has introduced key regulations, such as the Fertilizing Products Regulation (2019/1009) [9], the Circular Economy Action Plan [10], the Farm to Fork Strategy [11], the Zero Pollution Action Plan [12], and the Nutrient Management Action Plan [13]. These initiatives aim to enhance fertiliser efficiency, reduce greenhouse gas (GHG) emissions, and promote nutrient recovery for a more sustainable agricultural systems.

Key strategies from these policies include: (i) the establishment of nutrient management protocols to mitigate nutrient losses [1], (ii) the enhancement of nutrient use efficiency [14], and (iii) the proficient deployment of nutrient recycling technologies from biomass or other secondary raw sources for the production of fertilisers (herein referred to as bio-based fertilisers BBFs) [15–17].

Integrating circular economy practices into fertiliser production aligns with this third strategy by replacing conventional raw materials with residual biomass sources, such as post-harvest residues, livestock by-products, sewage, and food processing waste. This approach not only prevents nutrient losses and pollution, while minimises waste but also enables the recovery of essential nutrients (NPK) from organic waste streams using innovative nutrient recycling techniques such as anaerobic digestion, struvite precipitation or pyrolysis [15]. The choice of technique depends on factors like waste type, technological feasibility, and required product purity [15]. Beyond nutrient recovery, these technologies also facilitate the extraction of energy, water, and other valuable compounds, contributing to cost savings across the production chain [18]. The final products—such as bio-based fertilisers, biostimulants, and soil improvers—enhance soil health and crop yields while supporting the production of biofuels and other bio-based chemicals [15].

Many studies have evaluated the effectiveness BBFs (In this article, we adopted the concept of BBF as proposed by [16] as *"fertilizer product derived from renewable biomass related resources which purpose is to provide plants or mushrooms with nutrients or improve their nutrition efficiency"*. In addition, we recommend to follow the proposal delivered on the position paper of the 5 RUR08 sister Horizon projects DOI: https://doi.org/10.5281/zenodo.13969019 accessed on 13 October 2025. and the European Sustainable Phosphorus Platform (2023) https://www.nutrientplatform.eu/scope-in-print/spotlight/41-previous-spotlight/2308-what-does-the-term-bio-based-fertiliser-mean, (accessed on 13 October 2025)) in replacing mineral fertilisers, showing comparable agronomic performance to mineral fertilisers [19] improving soil quality [20] and reducing greenhouse gas emissions—both from lower direct N_2O emissions and decreased life-cycle energy use—when replacing mineral fertilisers [21]. They also allow for tailored formulations suited to specific crops [22]. Farmers in several European countries, such as Belgium, Denmark, France, and Germany, have shown a growing acceptance of BBFs [19,23].

Despite their potential, the lack of a clear definition for BBFs leads to regulatory inconsistencies and further research is needed to understand how market dynamics, policies, and consumer preferences influence BBF production and adoption [24]. Concerns also remain about quality standards and assurance processes in BBF production. Establishing a harmonised quality system is essential to ensure reliability, foster trust, and support the development of a stable BBF market [25].

The major concern with BBFs lies in their effectiveness and purity, although environmental impacts during production, storage, and field application also deserve attention. A robust evaluation methodology is required to consider all possible trade-offs [20]. A comprehensive evaluation of these impacts enables a more accurate understanding of their potential effects on soil health, water and air quality, human well-being, and overall ecosystem integrity. Understanding the environmental footprint of bio-based fertilisers helps us mitigate adverse effects such as nutrient runoff, GHG emissions, and soil degradation while maximising their benefits in terms of crop productivity and resource efficiency.

The environmental impact of BBFs has been evaluated employing various methodologies and approaches, each designed to assess specific aspects of their environmental performance. The agronomic performance evaluation has become a common practice to evaluate the effects of BBFs on crop yields, nutrient uptake, and soil quality. These tests provide insight into the potential of BBFs to replace mineral fertilisers while maintaining or improving agricultural productivity [26,27]. They also help to identify any potential impacts related to nutrient leaching or runoff [18]. Additionally, both chemical analyses to identify potential contaminants and ecotoxicological methods—such as standardised bioassays with aquatic and terrestrial organisms—have been used to assess the potential toxicity of BBFs to agricultural soils and organisms [28]. Lastly, some authors have measured the emissions of GHG (N_2O, CO_2, CH_4) after applying BBFs to assess their environmental impact compared to mineral fertilisers. These measurements help us to understand the potential contribution of BBFs to climate change mitigation or exacerbation [14,29,30].

LCA is increasingly being used to answer environmental questions, providing a comprehensive evaluation of BBFs production from the perspective of environmental sustainability [31]. LCA is capable of measuring the potential environmental impacts caused by products through their entire life cycle by analysing each stage of production or performance. Moreover, it allows the comparison between different products or processes and quantitatively recognises different hot spots based on proven causalities [32]. However, some LCA limitations include its reliance on assumptions and scenarios (simplifying the complex processes), necessity for large datasets to obtain robust results, and the different scopes that the selected studies might have, which can affect the results [33–35].

For this reason, it is important to recognise that individual methods alone are insufficient for a full assessment; only by combining approaches, such as coupling LCA with agronomic performance or ecotoxicological evaluations, can a comprehensive evaluation of BBFs be achieved. This evaluation should consider both the potential benefits and risks or drawbacks associated with BBFs. Nonetheless, these are dimensions not fully covered by the LCA. There is a knowledge gap in the identification of the methodologies and results of the environmental trade-offs of the production and consumption of the BBFs. Moreover, there is a need to summarise the pieces of evidence about this topic in the scientific literature.

The objective of the present study is to provide a comprehensive understanding of the potential environmental impacts and benefits associated with the BBFs production and use. As a novel contribution, this article includes a hybrid approach that integrates bibliometric and content analyses. To the best of the authors' knowledge, this is the first study to examine the evolution of the literature on BBFs, the environmental concerns associated with their use, and the scientific methodologies to assess these impacts.

2. Methodological Approach

A two-step literature review was developed to identify the main environmental concerns and other sustainability indicators about the BBFs. The obtained database of scientific publications was used to develop a bibliometric analysis. Additionally, the 20 most cited articles (see Section 2.3) were thoroughly analysed to determine priorities and identify information gaps based on scientific outputs.

2.1. Main Sentence Construction

Table 1 summarises the two queries carried out in the Scopus® database, including the publications until 9 December 2024. The first query aimed to identify commonly used terminology in scientific publications, ensuring consistency in its application across meetings, conferences, and international guidelines and regulations. The second query was oriented to the environmental impacts, benefits or methods along the BBF life cycle (from the production to its application in the field). Both queries were crossed by combining field codes, Boolean and proximity operators to develop a main sentence and generate a compilation of publications.

Table 1. Terms of queries for the main sentence.

Terms of BBFs	Terms of Environmental Impacts
OR (“bio-based fertili*”, “biobased fertili*”, “recycling derived fertili*”, “nutrient recovery”, “waste-based fetili*” “alternative fertili*”, “waste-to-fertili*”, “nutrient recycling”, “recycled fertili*”, “recovered nutrient”, “recover* nitrogen”, “recover* phosphorus”, “recover* carbon”, “fertili* product”, “fertili* products”)	OR (“environmental impact*”, “environmental assess*” “environmental indicator*”, “environmental analys*”, “environmental metric*”)

For crossing both queries the operator AND was used, that is, a term of each query had to be contained in the publication to be considered (The complete sentence query used in Scopus was TITLE-ABS-KEY(((“bio-based fertili*” OR “biobased fertili*” OR “recycling derived fertil*” OR “nutrient recovery” OR “waste-based fetili*” OR “alternative fertili*” OR “waste-to-fertili*” OR “nutrient recycli*” OR “recycled fertili*” OR “recovered nutrient” OR “recover* nitrogen” OR “recover* phosphorus” OR “recover* carbon” OR “fertili* product” OR “fertili* products”)) AND ((“environmental impact” OR “Environmental assess*” OR “environmental indicator” OR “environmental analys*” OR “environmental metric*”)))).

2.2. Data Collection, Processing and Cleaning

The query search was limited to results containing specific terms in the title, abstract or keywords. The selection criteria for including publications in the final list were the following filters:

- Document type: Only original (peer-reviewed) papers and reviews. Grey literature was not included.
- Language: Publications entirely written in English were maintained.
- Period: Limited from 2001 to 2024 (the last update was developed on 9 December 2024).

As a preliminary result, a total of 369 sample publications, including abstracts, author keywords, bibliographical, citation, and reference information of each one, were obtained. The next step consisted of a manual refinement process, which involved carefully reading the titles and full abstracts to exclude publications that did not match the search terms related to the production or application of BBFs and their environmental impacts. Hence, only 247 papers were included in the final database, saved in the format Bibtext (*.bib) for further analysis (See complete database in Supplementary Materials SM1). Finally, the database was systematically analysed in two ways: (a) bibliometric analysis and (b) in-depth analysis. A summary of the search results and the different phases of the systematic review are shown in Figure 1.

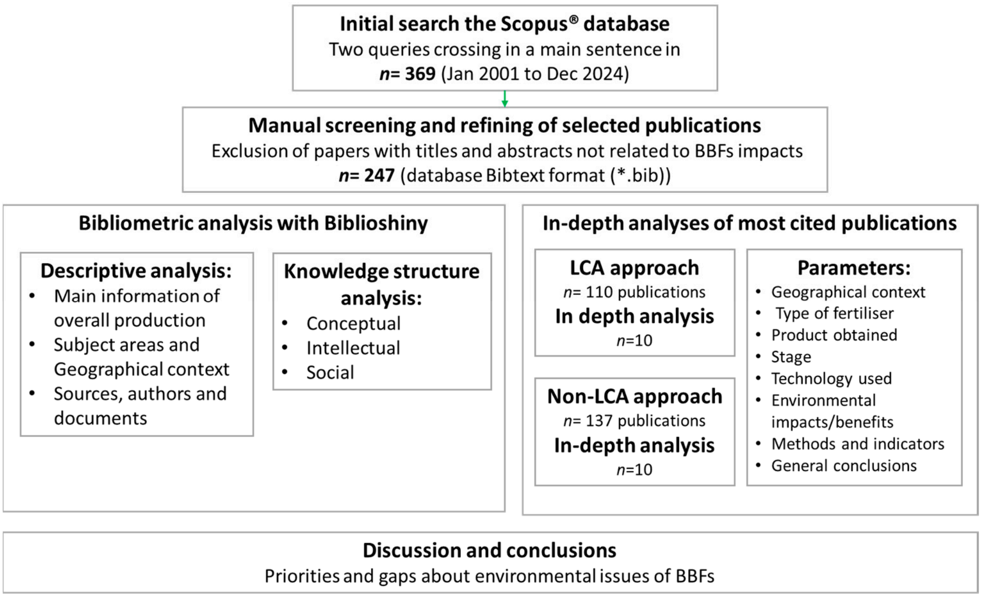

Figure 1. Workflow applied for the systematic review of the environmental concerns of bio-based fertilisers (BBFs). The database was exported in BibTeX format (*.bib), where the asterisk denotes any file with the .bib extension.

2.3. Bibliometric Analysis

The bibliometric analysis was used as a statistical tool to identify patterns in the current research on the topic of interest [36]. In the first instance, different bibliometric parameters, such as publication evolution and citation analysis of journals, publishers and authors, were used to find trends in the evolution of publications.

Moreover, the refined database with n = 247 documents was analysed in the Biblioshiny app, a shiny web-based, user-friendly app to use the Bibliometrix 5.0 R package [37]. This package can analyse data using three structures of knowledge: conceptual (the main themes and trends in science), intellectual (how an author's work influences a scientific community), and social (the interactions between authors, institutions, and countries). This analysis allows for the identification of critical elements in the literature and provides insights for future research by visualising the relationships between these critical elements.

2.4. In-Depth Content Analysis of the Most Influential Publications

During the manual filtering of the main database (n = 247), the LCA approach was identified frequently as a key approach for evaluating potential environmental impacts. Consequently, the dataset was stratified into two distinct categories: (i) publications employing the LCA approach and (ii) publications utilising alternative methodologies (non-LCA). Then, the 10 most influential (most cited) original publications (excluding reviews) of each category (a total of 20 publications) were selected to conduct a content analysis aimed at identifying cognitive schemes to extract in-depth insights from the literature [38,39]. The information extracted pertained to the geographical context, type of fertiliser product obtained, production technology used, experimental phase, environmental impacts/benefits, methods and indicators used, and general conclusions.

Finally, the combination of descriptive and content analysis allowed us to answer the research questions about the trends, evolution of production, the authorships affiliation, the journals of the publications, the main topics, the topics identification and evolution, the formulation of knowledge gaps and priorities in terms of environmental trade-offs.

3. Results and Discussion

3.1. Descriptive Analysis

3.1.1. Overall Production and Main Information

The bibliometric analysis conducted in the Scopus® database shows that research on BBFs has increased in recent years. The most significant numbers were the research articles (211) and the review articles (36). Based on the productivity of publications (number of publications over time), two periods can be distinguished (Figure 2). Period A (from 2001 to 2015) exhibits a low production rate, averaging 2.6 documents per year. Period B (from 2016 to 2024) shows a continuous annual increase (almost 10 times more than the previous period) in the number of publications registered, with an average of 23.11 documents per year. This growth coincides with the introduction of the concept of Circular Economy (CE) by the European Commission [40] (EC, 2015) and the CE package, which incentivises the use of by-products (derived from biowastes) in fertiliser regulation. Regarding the number of citations, there is a marked and exponential growth trend; the year with the highest number of citations was 2016, accumulating 1365 overall citations. For 2024, production and citations are less than in previous years due to the analysis performed before finalising the entire year, but the estimated production will be around 50 articles and more than 1700 citations which could confirm this increment in the growth rate.

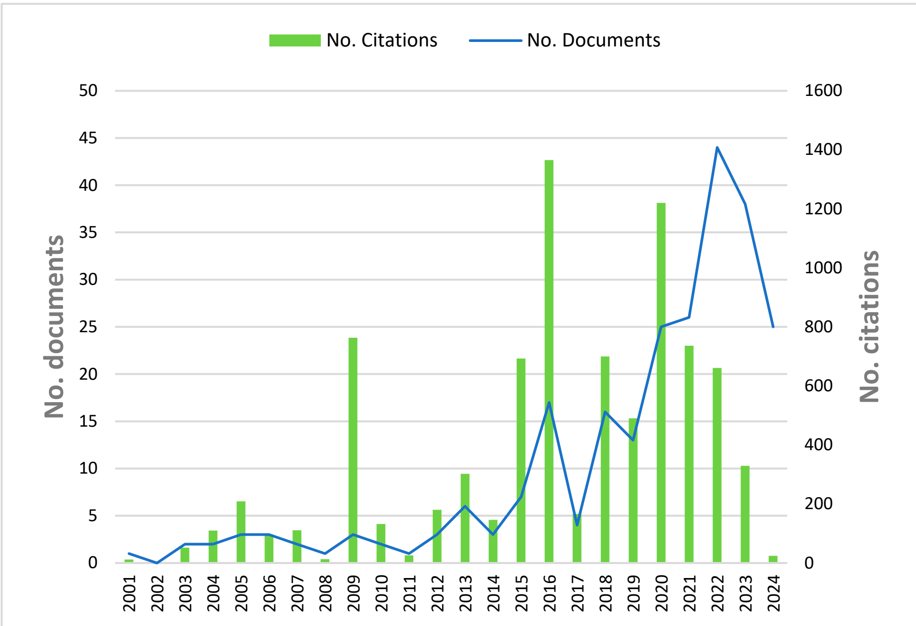

Figure 2. Year-wise publication and citation about BBFs during the period January 2001 to August 2024.

3.1.2. Subject Areas and Geographical Context

The annual growth rate was 15%, published in 92 different sources. 76% of the publications were aggregated into five subject areas. (i) Environmental Sciences (41%) is the primary subject due to the publications in this field reporting the possible environmental impacts of using these recovery technologies, (ii) energy (13%) with a majority publication about LCA and biorefineries, (iii) engineering (10%) where the publications focused on biochar and manure valorisation technologies, (iv) agricultural and biological Sciences (6.6%) reported the same focused mainly on the evaluation of the new technologies and the effects caused by the application of the products, respectively, and (v) chemical engineering (6.2%) subject area cover the feasibility of different biorefinery technologies for producing BBFs.

The geographical analysis of scientific production revealed a significant concentration of research efforts in European countries (Figure 3a), primarily supported by funding from the European Commission and national sources. Within Europe, Spain leads with 38 publications, followed by Belgium, Italy, and Sweden, each contributing 21 publications. The United States (47) emerges as the primary contributor within the North American region and globally as a single nation, with research predominantly funded by agencies such as the National Science Foundation, the U.S. Department of Agriculture, and the National Institute of Food and Agriculture. In Asia, China stands out as the leading contributor with 27 publications, primarily financed by the National Natural Science Foundation of China and the National Key Research and Development Program of China.

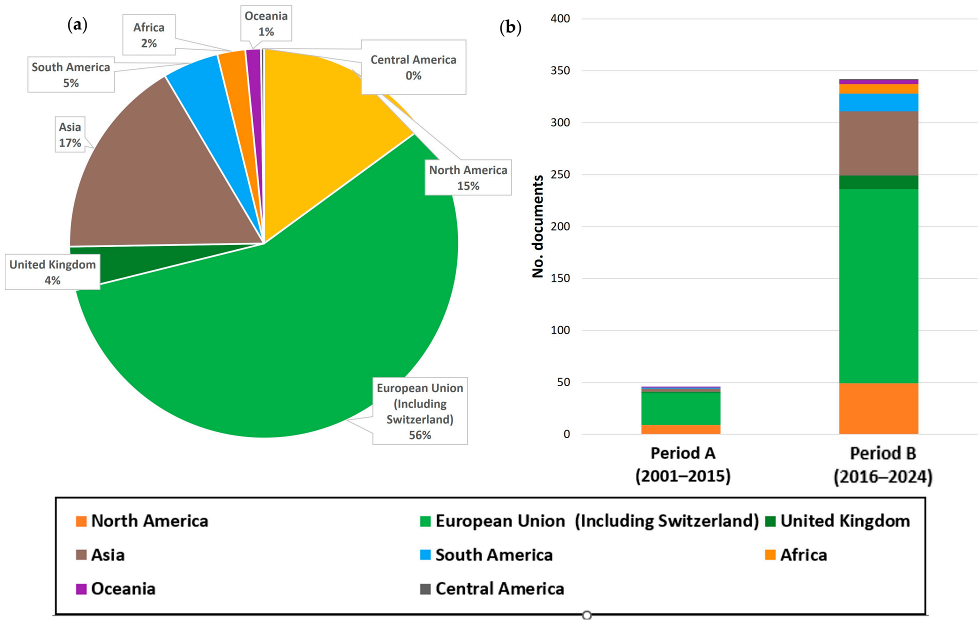

Figure 3. Geographical background of BBFs environmental impact studies represented in percentage (**a**) and divided into production periods (**b**).

When comparing the two production periods, a substantial increase in overall scientific output is evident across most regions. European countries dominated research production in both periods, experiencing a remarkable growth of five times, from 31 publications in Period A to 187 in Period B (Figure 3b). During Period A, Sweden led research emphasising topics such as nutrient recovery from food waste, wastewater, and organic waste. In Period B (2015–2023), Spain emerged as the leading contributor, concentrating on N and P recovery and the effects of BBFs on agricultural lands. In North America, the number of publications increased from 9 to 39, with the United States leading in both periods, primarily investigating phosphorus recovery and digestate production. Asia also registered a significant increase both in the number of publications (from 3 to 62) and in its overall share of global research, mainly driven by China's work on fertilising products derived from wastewater and swine manure.

3.1.3. Sources and Authors

Table 2 presents the top 10 most productive sources related to the central topic. Among these sources, the journal Science of the Total Environment (STOTEN) stands out with 32 publications (8%) covering alternative fertiliser production from wastewater treatment, human urine, agricultural wastes, and manure. Then, the Journal of Cleaner Production (JCEN), with 26 publications (7%), focused on nutrient recovery technologies, particularly phosphorus, from wastewater and manure treatment. Furthermore, the Journal of Environmental Management (JOEM) (12 publications, 5%) emphasises topics such as nutrient recovery (mainly nitrogen) from manure and digestate revalorisation, its impacts, and potential GHG emissions due to the use of these products. It is important to note that a significant number of these studies employ LCA as a key methodology for evaluating environmental impacts. Finally, the most cited journals are also highly respected and are in the top quartile. Comparing this list with the most cited sources, 80% of them are included in the top 10, except for the "Journal of Environmental Management" and "Sustainability" (Switzerland), which are ranked 11th and 14th, respectively. This indicates that these 10 resources listed represent the core of the most relevant information on the subject.

Table 2. Top 10 journals with the greatest number of articles and their local impact regarding bio-based fertilisers and their environmental concerns.

Sources	Publisher	No. Publications	H Index	Impact Factor	Cite Score	Quartile	Most Cited Rank
Science Of the Total Environment	Elsevier	32	11	10.754	16.8	Q1	4th
Journal Of Cleaner Production	Elsevier	26	16	11.072	18.5	Q1	3rd
Journal Of Environmental Management	Elsevier	12	5	8.91	13.4	Q1	11th
Waste Management	Elsevier	10	7	8.816	15.1	Q1	5th
Water Research	Elsevier	10	8	13.4	19.8	Q1	2nd
Resources, Conservation and Recycling	Elsevier	9	6	13.716	20.3	Q1	9th
Sustainability (Switzerland)	MDPI	9	3	3.9	5.8	Q1	14th
Bioresource Technology	Elsevier	7	6	11.889	19	Q1	1st
Chemosphere	Elsevier	7	4	8.943	13.3	Q1	7th
Environmental Science and Technology	ACS	7	4	11.357	16.7	Q1	6th

In the discussion about the potential environmental and human health impacts of BBFs, 1101 authors have contributed over the years 2001 to 2024. Meers, E., Adani, F., and Sigurnjak, I. are the top three authors with the highest number of publications and citations achieved per year (Figure 4). These three authors began their significant scientific production in period B (2016–2024), coinciding with a notable increase in publications on the topic and they have continued publishing, with 2022 being the most prolific year. Regarding period A, three authors are responsible for the largest number of publications: Jonsson, H, Martin, M and Moreira, M.T.

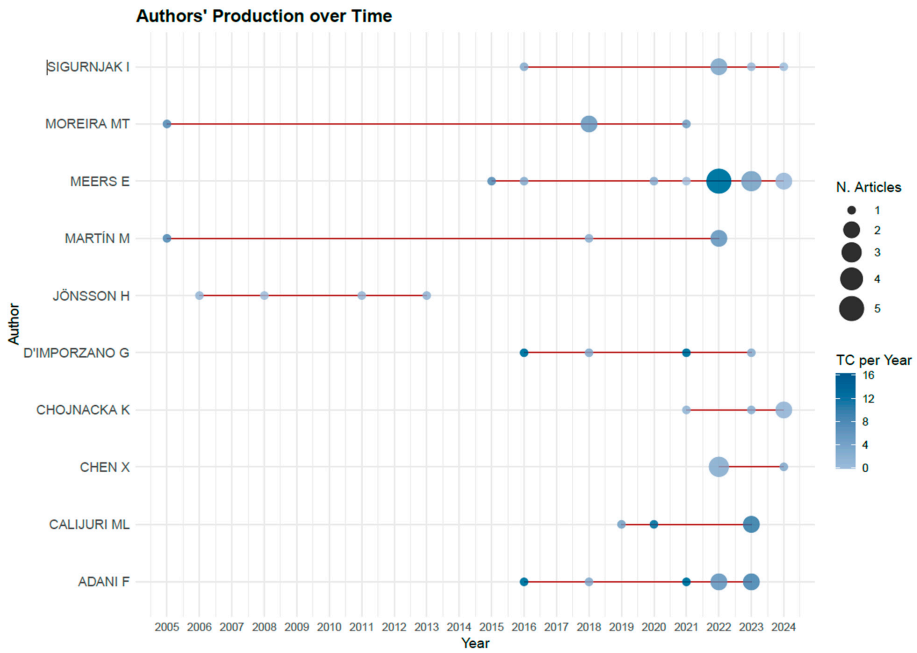

Figure 4. The top 10 authors' production from 2001 to 2024 on BBFs and their environmental impacts. TC: total number of citations.

Furthermore, an analysis of the most influential authors, in connection with the primary research topics and the journals where their work is published (Figure 5), reveals that the research predominantly focuses on nutrient recovery (using different technologies and feedstocks), with a strong emphasis on the LCA methodological approach. This focus is closely aligned with the journals in which these studies are published.

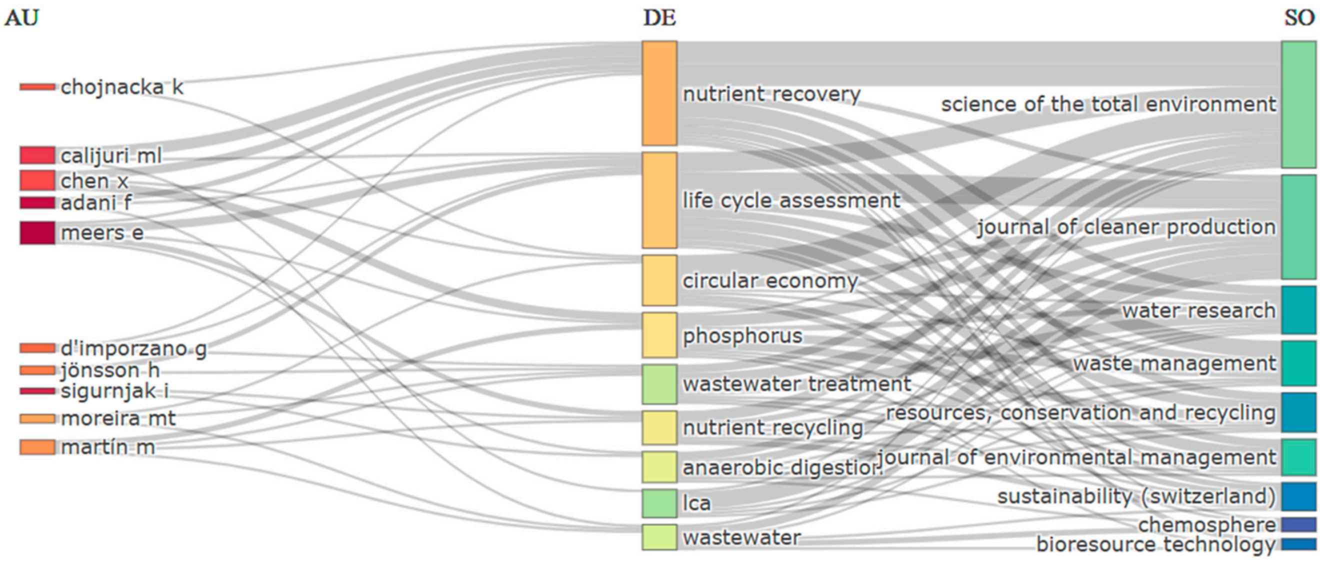

Figure 5. Three-field plot illustrating AU: influential authors (left), DE: research topics (middle), and SO: Sources (right). Colours are automatically assigned and do not indicate specific categories.

3.2. Structures of Knowledge

3.2.1. Conceptual Structure and Thematic Evolution

The conceptual structure analysis revealed the relationships between key concepts and terms across the publications, effectively mapping the focus of current scientific inquiry [37,41]. After using Multiple Correspondence Analysis (MCA) to analyse 713 keywords, we identified four clusters (Figure 6a). The first cluster focused on BBFs production technologies, nutrient recovery, waste sources, and potential environmental impacts (main terms: "nutrient recovery", "life cycle assessment" and "phosphorus"). The second cluster centred on energy recovery technologies and their techno-economic assessment (main terms: "anaerobic digestion", "waste management" and "energy recovery"). The third cluster reflected a significant number of studies on phosphorus recovery from human urine (main terms: "source separation", urine, and "recovery"). The fourth cluster encompassed topics related to the performance of BBFs and their effects on soil fertility (main terms: "hydrothermal carbonisation", "swine" and "hydrochar"). Additionally, terms positioned closer to the centre of the graph are considered central to the research focus, with "nutrient recovery", "life cycle assessment", "phosphorus" and "circular economy" emerging as the primary themes.

By analysing the evolution of topics over time (Figure 6b), it has been possible to determine a core of basic terms on which research has focused. The most recurrent topic over time has been the content of heavy metals in BBFs. Additionally, terms such as "phosphorus", "anaerobic digestion", "fertiliser", and "nitrogen" (2016 to 2022) indicate that research is focused on widely used technologies for obtaining BBFs and two of the most studied nutrients. Starting in 2018, new topics such as "life cycle assessment", "nutrient recovery", and "resource recovery" have begun to emerge, suggesting a more complex and holistic approach to evaluating the possible environmental effects produced by BBFs. In the last two years, topics such as the "circular economy" and "climate change" have also started appearing in scientific publications, indicating the interest of various regional initiatives in revaluing and implementing these products within the supply chains of the agri-food sector.

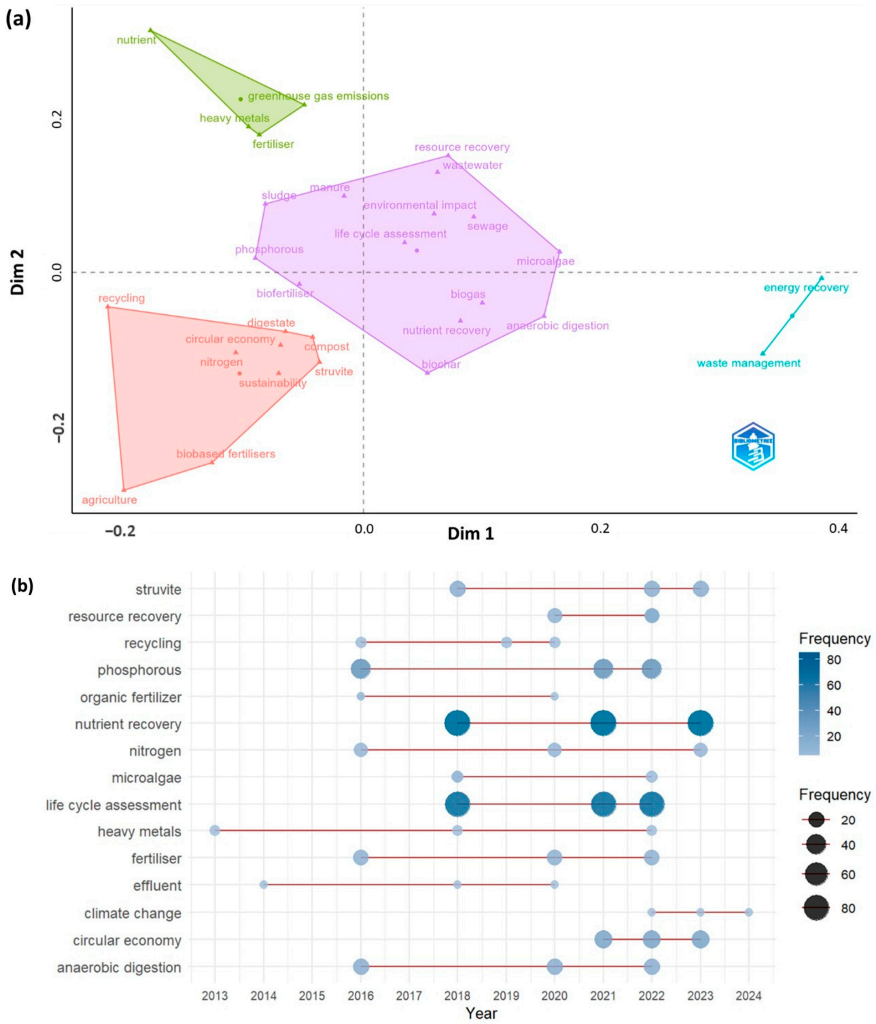

Figure 6. (**a**) Two-dimensional conceptual structure map based on multivariate analysis. The axes (Dim 1 and Dim 2) represent principal components capturing the highest variance in term co-occurrence.. Triangles represent keywords; proximity indicates co-occurrence. Colours show thematic clusters, and points mark central terms in each group. Dominant themes include nutrient recovery, recycling, circular economy, and waste valorisation. (**b**) Timeline of trend topics from 2013 to 2024. Circle size and color intensity represent the frequency of each term per year, revealing the evolution and prominence of key research topics over time.

3.2.2. Authors Publications and Topics That Influence the Scientific Community

A co-citation network of publications was developed to detect changes in paradigms or schools of thought [42] about the different research areas in BBFs production and application. Six clusters can be seen in the network (Figure 7). The three publications with the highest number of co-citations (grouped in the red cluster) were published by (i) Amann et al. review of the environmental impacts of phosphorus recovery from wastewater [43], (ii) Bradford-Hartke et al. published an original research on the environmental benefits and burdens of phosphorus recovery from municipal wastewater [44], and (iii) Maurer et al. conducted a comparative analysis of the environmental and economic performance of various technologies for phosphorus recovery from wastewater. Their findings highlight a clear dominance of scientific research focused on phosphorus recovery from wastewater systems [45]. Subsequent publications are focused on LCA (green cluster), treatment processes for source-separated urine (yellow cluster) [46], and nutrient recovery (N and P) from digestate (purple and blue clusters) [47,48].

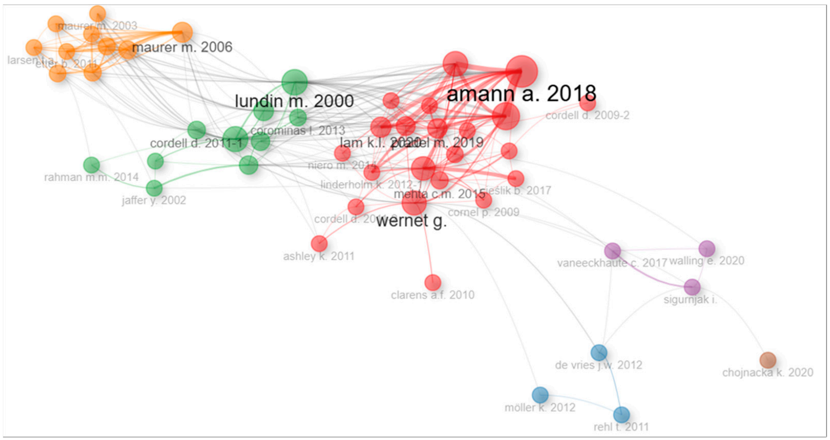

Figure 7. Co-citation network of publications. Node size reflects citation frequency, edges indicate co-citation strength, and colours represent thematically related clusters detected algorithmically, highlighting the core and peripheral research themes in the field. Individual citations are not included here, but all references are properly listed in the Supplementary Materials SM. 3.2.3. Collaboration Networks Between Authors, Institutions and Countries.

The co-authorship network provided valuable insights into the various interactions and collaborations among authors, resulting in the identification of nine distinct collaboration groups (Figure 8a). A total of 37 authors were identified across the different groups, revealing a strong network of collaboration within individual clusters (represented by different colours) and incipient or no collaboration between them. However, when analysing collaborations based on the author's affiliation (Figure 8b), a broader network of interactions between different groups emerges. The analysis reveals that the majority of these collaborations are concentrated among European research institutions (universities and research centres), with additional, though less frequent, partnerships involving institutions in the United States and China.

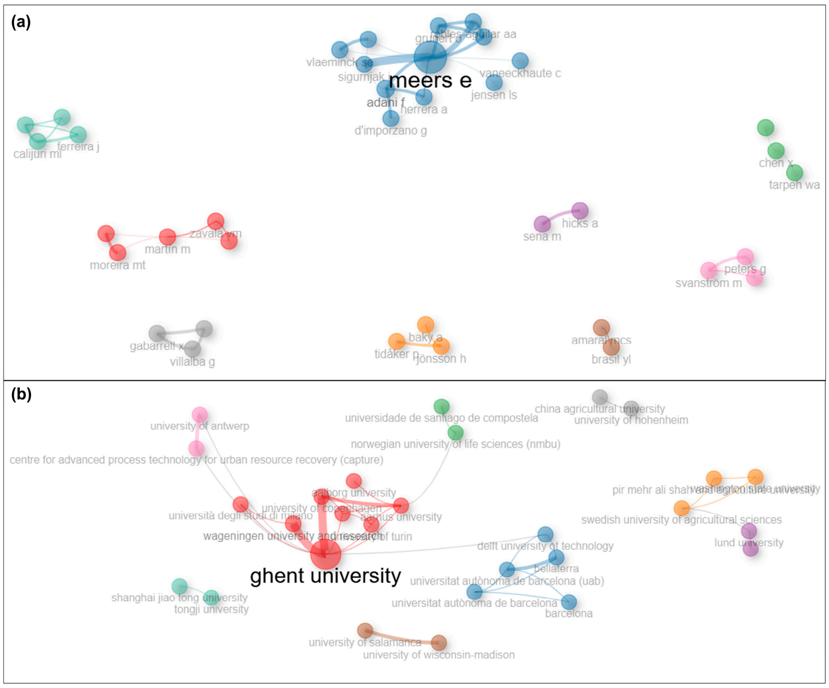

Figure 8. Collaboration networks between authors (**a**) and institutions (**b**). Nodes represent authors or institutions, with node size proportional to the number of collaborations (co-authorships). Node colours indicate distinct collaboration clusters identified through co-authorship network analysis.

3.3. In-Depth Analysis

The number of citations is a key metric in bibliometric studies, as it highlights the most influential, well-studied, and extensively developed topics within a research field. In this study, the LCA approach accounted for 110 publications (45%), including 12 reviews and 92 original research publications. Conversely, the non-LCA approach comprised 137 publications (55%), with 24 reviews and 113 original research publications. The in-depth analysis focused exclusively on original research publications to investigate methodological trends, discussions (including limitations and future research directions), sensitivity areas, and opportunities related to the environmental concerns of BBFs. This approach aimed to establish a more targeted conceptual framework for identifying research priorities.

3.3.1. Studies Using a Non-Life Cycle Assessment (Non-LCA) Approach

Table 3 presents the 10 most cited publications in the non-LCA category. Most of these studies were conducted in Europe (60%), with the rest originating from North America and Asia. These publications employed diverse methodological approaches to evaluate BBFs, but no common guidelines or consensus emerged. A significant portion of the studies (60%) focused on characterising BBF products such as digestate, struvite, and hydrochar, as well as assessing the emerging technologies used to produce them. The remaining 40% was dedicated to exploring the production processes and agronomic performance of BBFs.

The primary raw materials used for producing BBFs were human urine, sewage sludge from wastewater treatment, and livestock manure (from pigs and poultry). Among the technologies reviewed, those integrated with wastewater treatment systems were particularly prominent, especially innovative methods for recovering human urine to precipitate struvite [49–52]. Anaerobic digestion also frequently appeared as a key technique, typically used in biorefineries for biogas production, where both the solid (digestate) and liquid fractions are repurposed to create BBFs. Struvite and digestate (both liquid and solid fractions) were the most prevalent products used as BBFs. The percentage of publications was the same in the products rich in P and N.

Heavy metal content and the presence of organic pollutants were among the most frequently cited environmental impacts in studies focusing on struvite precipitation techniques [51,53] and the production of BBFs from microalgae cultivated in wastewater [54]. GHG emissions, including ammonia, N_2O, and CO_2, were the most significant environmental concerns in studies evaluating digestates, particularly during their application in agriculture [55,56]. Notably, the study by [57] was the only one to identify bad odour as a potential impact from surface applications of digestate and its liquid fraction. Additionally, two studies recommended future research to develop LCA to identify the potential environmental impacts of both the technologies used and the performance of the resulting BBFs [56,58].

The methods and indicators used varied significantly among all the studies analysed; in most cases, direct measurements, highly sensitive techniques, and account techniques were used. This variety made it difficult to identify a general trend or consensus for evaluating the different BBFs, even when they were the same products. However, certain patterns emerged: some studies focused on product characterisation using laboratory analytical methods (chromatography, ICP, spectroscopy, etc.) [51,53,58]. Others employed mathematical [52] or computer modelling [49,56] to predict potential outcomes or benefits of the BBFs production or application. Additionally, some studies gathered data through interviews and analysis provided by technology operators [50,55]. A significant number of studies that appeared in the list incorporated robust statistical analysis with multiple representative replications to enhance the reliability of their results. At last, it is noteworthy that in many (non-LCA) studies, the approach to assessing and monitoring potential environmental impacts tends to be fragmented or very specific. A comprehensive methodology that considers multiple factors, such as technology development, agronomic and biological performance (in terms of biodiversity), and the diverse ecosystem interactions of BBFs, is rarely applied. LCA may offer some insights in this regard. Notably, the study by [54] stands out as the only one that presents a methodology capable of addressing all these environmental aspects through a holistic approach.

3.3.2. Studies Using the Life Cycle Assessment (LCA) Approach

Table 4 presents a summary of the results from the top 10 most cited publications within the LCA sub-list. The research was predominantly conducted in Europe (80%), with significant contributions from countries such as Spain, Denmark, Belgium, and Italy. These studies primarily focused on the production processes and agronomic performance of BBFs, and only two studies were dedicated to assessing the impacts caused by the storage [59] and transport [60].

Most of the analysed publications (70%) utilise effluents or sludges from wastewater treatment systems as the primary raw material. Anaerobic digestion was the most frequently applied technology for producing BBFs from sludge [61–63]. Additionally, three studies were focused on agricultural livestock substrates [59,60] such as pig slurry [64] for obtaining BBFs. Another alternative technology used in treating wastewater effluents is the precipitation of struvite, and perhaps a more innovative approach involves precipitating this mineral through the recovery of human urine was applied by [65,66]. Finally, it was possible to verify through the analysis of technologies and products obtained (BBFs) and their application in some cases, that the research has mostly focused on obtaining BBFs rich in phosphorus, as suggested by the bibliometric analysis and only a small number of publications have focused on other nutrients such as nitrogen [59].

In the context of environmental concerns reported, LCA studies typically address multiple environmental impact categories, whereas non-LCA studies tend to focus on a single environmental issue. The impact categories most frequently mentioned by authors included: (i) global warming, typically linked to the increased energy consumption required for the production, transportation, and application of BBFs, driven by machinery (digesters, heaters, and tractors, etc.); (ii) eutrophication, resulting from the runoff or leaching of nitrogenous or phosphate compounds; (iii) acidification, associated with the release of ammonium; (iv) human toxicity, which encompasses the emission of pollutants into the atmosphere, soil, or water; and (v) heavy metal content, where depending on the source material, the concentration and accumulation of metals may exceed permissible limits, posing risks to human health [15,20]. However, several authors suggest that environmental impacts can be mitigated by generating energy, such as biogas, during the production of BBFs, which reduces reliance on fossil fuels [67]. Additionally, the application of BBFs can enhance soil quality and health, further contributing to environmental sustainability [20].

Table 3. Top 10 most relevant documents (ordered by number of citations) using non-LCA approach.

No	Author/No. of Citations/Source	Country/Region	Technology/Product	Stage(s)	Environmental Concerns	Method of Assessment/ Indicators	Conclusions
1	Egle [50]/259/ Resources, Conservation and Recycling	Europe	P recovery processes from different sources of wastewater. 1. Technologies based on: Crystallisation, Precipitation, 2. Ion exchange and 3. Others.	Production	**Impacts** • Urine separation. Pharmaceuticals and hormones are present in very small Sewage sludge. Heavy metals, organic pollutants, pharmaceuticals, and pathogens. Its acceptance as an agricultural fertiliser is low and prohibited in some countries (e.g., Switzerland and the Netherlands).	Literature review, information from interviews of plant operators, researchers, and commercial companies, and by visiting existing plants.	Three main approaches for future phosphorus (P) recovery from sewage sludge ash (SSA): 1. No heavy metal removal: offers high recovery potential (85% of WWTP influent) and improved plant availability of P, but does not address heavy metal contamination. 2. Partial heavy metal removal: high recovery potential (85%) but uncertain plant availability, with potential improvement using sodium sulphate instead of chlorine compounds. 3. Nearly complete heavy metal removal: lower recovery potential (70%) but yields a final product with high plant availability or suitability for industrial use, such as in phosphoric acid production.
2	Riva [57]/146/ Science of the Total Environment	Italy	Untreated cattle slurry, using Anaerobic digestion Products: digestate and separate liquid fraction of digestate.	Production and application (different methods)	**Impacts** • Potential odour emissions in surface application. • Ammonia emissions when digestate is applied to the surface. **Benefits** Soil characteristics did not seem to be affected by fertiliser management in the short term.	Odour emissions [68] Ammonia emissions [69,70]	Results show sub-surface injection of digestate and its derivatives, applied both at pre-sowing and top dressing, achieved crop yields comparable to those obtained with urea. Additionally, this method significantly reduced ammonia emissions to levels similar to urea application. Moreover, the efficient use of digestate, coupled with its high biological stability from the anaerobic process, substantially mitigated odour impact.
3	Hou [56]/96/ Environmental Science and Technology	Europa	The main flows of nutrients embodied in animal manures and the possible manure treatment techniques (the most used in the 27 EU countries). 1. Solid−liquid separation. 2. Anaerobic digestion. 3. Acidification. 4. Biological aerobic N removal. 5. Composting. 6. Drying Incineration	Production and application	**Impacts** • Low recovery N fraction in nitrification–denitrification, incineration, and slow pyrolysis. **Benefits** • Anaerobic digestion decreases GHG emissions. • Slurry acidification, incineration, and pyrolysis are manure treatment technologies that reduce NH_3 and GHG emissions, with slurry acidification also increasing the nitrogen fertiliser equivalent value by approximately 25% compared to raw slurry.	MITERRA-EUROPE model calculates the nitrogen (N) and phosphorus (P) losses and GHG emissions on a deterministic and annual basis, using statistical data of agriculture at EU country and regional levels [71].	Anaerobic digestion and solid–liquid separation are the leading manure treatment technologies in Europe. AD is the most effective technology for reducing greenhouse gas (GHG) emissions among all treatment methods. AD and slurry separation have minimal impact on NH_3 emissions. Composting is practised on a smaller scale across various EU countries, generally reducing N_2O and CH_4 emissions compared to traditional storage. Scenario analyses also show alterations in GHG emissions due to manure processing. Technologies like acidification, thermal drying, incineration, and pyrolysis contribute to these changes. Some manure treatment technologies (such as incineration and slow pyrolysis) convert a significant portion of nitrogen (N) to dinitrogen gas, rendering it unusable for fertilisation.

Table 3. *Cont.*

No	Author/No. of Citations/Source	Country/Region	Technology/Product	Stage(s)	Environmental Concerns	Method of Assessment/ Indicators	Conclusions
4	Antonini [49]/87/ Chemosphere	Germany	Six urine-derived struvite fertilisers called MAP: magnesium ammonium phosphate. Five were produced in Germany and one in Vietnam.	Production and application (agronomical performance in a pot trial)	**Impact** • Acidification **Benefits** • Struvite increases plant growth due to the extra magnesium concentration. • There is a very low probability that struvite fertilisers exceed the permitted limits of heavy metals in the national regulation.Combined with other soil conditioners, urine-derived struvite covers magnesium and more than half of the phosphorus demand of crops.	Computer modelling to measure the nutrient equivalents (NEQs) and heavy metal fluxes [72].	The production technology had minimal impact on the final product's composition, with only a positive correlation between magnesium dosing and magnesium concentration. Struvite from urine collected in Europe and Asia showed no significant dietary effects. GHG tests demonstrated that fertilisers produced comparable or superior biomass yields and phosphorus uptake compared to commercial fertilisers. Environmentally, urine-derived struvite is safe and contributes less heavy metal to soil than other fertilisers, effectively meeting significant portions of crops' magnesium and phosphorus needs when used with other soil conditioners.
5	O'Neal [52]/95/ Water Research	USA	Hybrid anion exchange (HAIX) resin containing hydrous ferric oxide.	Production	**Impacts** • More energy consumption due to decentralised treatment needs more reactors. **Benefits** • Lees energy consumption on wastewater treatment	Phosphate selective resin Equilibrium isotherm models	The HAIX-Fe resin showed a non-linear relationship between solid-phase and solution-phase concentrations for phosphate sorption. Source-separated fresh and hydrolysed urine resulted in higher phosphate recovery and loading on the resin compared to end-of-pipe streams. Diluted urine had lower phosphate loading and required more resin for recovery. This suggests that phosphate recovery is more efficient from building-level wastewater streams compared to central treatment plant effluents. The next step is to develop an LCA for environmental and techno-economic assessment.
6	Bernstad [55]/87/ Waste Management	Sweden	Physical pretreatment of food waste in Sweden: 17 anaerobic digestion plants, four of them were analysed as study cases.	Production	**Impacts** • Contamination of digestate with particles > 2 mm. • Loss of methane • Lees energy consumption on wastewater treatment	Interviews	Screw press technology resulted in larger losses of biodegradable material and nutrients compared to dispersion technology. There was also a trade-off between higher particle sizes in biomass, which reduce refuse losses but may slow methane conversion. The study highlights an urgent need to improve the efficiency of physical pretreatment processes to enhance methane yield and nutrient recovery from food waste.
7	He [58]/78/Bioresource Technology	China	Food waste digestate (FWD) and Yard Waste (YW) were mixed for co-Hydrothermal Carbonization (co-HTC) with organic and inorganic catalytic systems	Production of hydrochar as a fuel and the water was used for nutrient recovery (N and P)	Not provided The authors recommend developing an LCA to track the environmental impacts.	Characterisation of hydrochar and process water Thermal analysis for using hydrochar as a fuel	The catalytic co-hydrothermal carbonization (co-HTC) process of food waste digestate (FWD) and yard waste (YW) offers a promising method for bioenergy production and nutrient recovery, contributing to circular economy and carbon neutrality. Inorganic method achieves a high carbon utilisation efficiency of 97.5%. However, further pilot-scale testing is needed to evaluate material flow, energy balance, and environmental impacts to confirm its practicality for commercial use.

Table 3. *Cont.*

No	Author/No. of Citations/Source	Country/Region	Technology/Product	Stage(s)	Environmental Concerns	Method of Assessment/ Indicators	Conclusions
8	Krähenbühl [51]/59/Science of the Total Environment	Nepal	Struvite production from source-separated urine	Production	**Impacts** • Heavy metals content • Increasing Energy consumption • CO_2 release with the calcination methods	Calcination with magnesite rocks Struvite characterisation	Magnesite rock is a promising magnesium source for struvite precipitation from source-separated urine in Nepal. Longer calcination times do not improve solubility but increase heating costs. Traditional kilns may lack the precise temperature control needed, but if more controlled kilns are used in Nepal, locally sourced magnesite could be an effective and economical magnesium source for struvite production.
9	Dong [53]/57/ Water Research	USA	Hybrid anion exchangers (HAIX), with doped ferric oxide nanoparticles (FeOnp) for removing phosphates from wastewater	Production	**Impacts** • Heavy metals content • Increasing Energy consumption • CO_2 release with the calcination methods	HAIX with a weak acid cation exchanger (WAC) to enrich phosphate and calcium in mild regenerants and precipitate both elements for recovery. Spectroscopic analysis.	The shift from chemical-driven to electricity-driven ion exchange processes could facilitate adoption in remote, decentralised systems. Future work will involve testing this method with real municipal wastewater and exploring more saline water sources to enable chemical-free production of mild acids and bases. The work supports the development of resource-efficient electrochemical regeneration processes and the design of suitable adsorbents for practical applications.
10	Suleiman [54]/50/Resources, Conservation and Recycling	Netherlands	Microalgae cultivated in wastewater as a biofertiliser	Production and application	**Impacts** • Increasing of N_2O and CO_2 emissions due to nitrification. • Possible pathogen presence	Soil sampling Plant productivity and quality GHG sampling (CO_2 and N_2O fluxes measured in chambers) Molecular analysis Pot test (agronomical performance)	Microalgae from black water serve as an effective biofertiliser, enhancing plant growth. The use of microalgal biofertiliser increases N_2O and CO_2 emissions, primarily due to nitrification. Different nitrogen sources influence microbial communities in soil and rhizosphere, with plants playing a significant role in shaping microbial populations during growth stages. While microalgal biofertiliser supports nutrient cycling, management practices to reduce nitrification and N_2O emissions are crucial for sustainability. Further research is needed to assess potential pathogen risks in these residues.

Table 4. The top 10 most relevant documents (by number of citations) on the LCA approach.

No	Reference/Citation/Source	Country/Region	Technology/Product	Stage	Environmental Concerns Highlighted	Method of Assessment/Indicators	Conclusions
1	Hospido [62]/189/International Journal of Life Cycle Assessment	Spain	Sludge treatment to obtain agricultural fertilisers through 3 scenarios. Anaerobic digestion Incineration Pyrolysis	Production and land application.	**Impacts** • Acidification, global warming, and human toxicity. • Heavy metals. • Pathogens and organic pollutants. **Benefits** • Recovering energy through pyrolysis	LCA (SimaPro 5.1) Impact categories: Eutrophication, Stratospheric ozone depletion, Global warming, Acidification, Photo-oxidant formation, Depletion of abiotic resources, and Human toxicity.	Further research is needed to determine plant uptake and leaching of heavy metals from sludge in agricultural soils. Efforts to improve valuable by-products and prevent nutrient loss are ongoing. The selection of a sludge management strategy should be site-specific and consider environmental, social, and economic factors for long-term sustainability. Land application of digested sludge is seen as a viable option, but efforts should focus on minimising heavy metal content.
2	Arashiro [61]/171/Science of the Total Environment	Spain	1. High-rate algal ponds (HRAP) system for wastewater treatment (biogas production by anaerobic digestion) 2. HRAP system for wastewater treatment (biofertiliser production)	Production and application of digestate as fertiliser.	**Impacts** • Climate change • Ozone layer depletion • Photochemical oxidant formation • Fossil depletion	LCA (SimaPro8) - ReCiPe midpoint method. - Sensitivity analysis. Economic assessment.	HRAP systems coupled with biogas production were found to be more environmentally friendly than those coupled with biofertiliser production across various impact categories. HRAP systems coupled with biofertiliser production were observed to be the most cost-effective alternative for wastewater treatment in small communities, especially when implemented in warm climate regions.
3	Ishii [66]/150/ Water Research	USA	Urine recovery and struvite precipitation A: Baseline B: Urine recovery and struvite precipitation with Magnesium oxide (MgO) C: Urine recovery and struvite precipitation with Magnesium oxide (MgO) + Sodium phosphate (Na_3PO_4)	Production.	**Impacts** • Eutrophication. • Electricity increases emissions.	LCA (SimaPro 8.0.3.14 Ecoinvent and USLCI. - All the impact categories are included. - TRACI method [73]. 3000 iterations modelled in the Monte Carlo module.	Scenario B showed the smallest environmental impact compared to Scenarios A and C. The economic evaluations found relatively equal costs among the three scenarios. The environmental impact of Scenario A was mainly due to high electricity usage at the centralised wastewater treatment plant. While Scenario C allows for high recoveries of phosphorus and nitrogen as urine-based struvite fertiliser, the manufacturing chemicals required for these precipitation methods have substantial upstream impacts.
4	Medina-Martos [63]/113/Journal of Cleaner Production	Spain	1. Hydrothermal carbonization and anaerobic digestion to treat sewage sludge. 2. Standalone anaerobic digestion	Production	**Impacts** • Terrestrial eutrophication • Freshwater eutrophication • Marine eutrophication, • Photochemical ozone formation **Benefits** • Highly dependent on hydrochar utilisation	Process modelling and simulation in Aspen Plus®. Techno-economic analysis framework. LCA using Impact Categories recommended by ILCD guidelines: Global warming, Acidification, Respiratory inorganics, Human toxicity cancer effects, and Human toxicity non-cancer effects.	Integrating hydrothermal carbonization (HTC) with anaerobic digestion (AD) enhances energy recovery from sewage sludge (28% vs. 14%) and improves life cycle environmental performance notably reducing global warming impacts from 72 to 18 kg CO_2-eq per ton of sludge. Economic challenges, including a 42% higher treatment cost compared to conventional AD. A possible drawback at a policy level is the new trend towards higher nutrient recycling, which may produce legal barriers to hydrochar.

Table 4. *Cont.*

No	Reference/Citation/Source	Country/Region	Technology/Product	Stage	Environmental Concerns Highlighted	Method of Assessment/Indicators	Conclusions
5	Oldfield [59]/106/ Journal of Environmental Management	Belgium, Italy, and Spain	1. Compost 2. Biochar Biochar-compost blend (1:9 ratio)	Production, crop production (application) and transport.	**Impacts** • Global warming. • Acidification (biochar had the lowest impact at all sites). • Eutrophication. **Benefits** • Not evaluated because no appropriate assessment methodologies are available in LCA. • Control soil erosion and regulate soil moisture balance, • Biochar potentially regulates soil moisture balance.	LCA (GaBi v.6 software) - Midpoint methodology CML [74]. Contribution analysis - Sensitivity analysis [75].	Biochar, compost, and biochar–compost blends were found to be environmentally beneficial compared to mineral fertilisers in terms of global warming potential, eutrophication potential, and acidification potential. The study concluded that a one-size-fits-all recommendation cannot be developed for Europe, and site-specific studies are needed continually. All three treatments showed comparative yields to mineral fertiliser, and producing a blended product has the potential as an alternative in climate-smart agriculture. Both approaches showed that biochar, compost, and biochar-compost blend resulted in a cumulative lower environmental impact compared to mineral fertiliser alone. Careful selection of feedstock is crucial for commercial development from a circular economy perspective.
6	Bisinella de Faria [65]/106/Water Research	Scenario-based on a wastewater treatment plant (WWTP) in East Europa	Urine Source-Separation in five WWTPs scenarios	Production of struvite and agricultural application.	**Impacts** • Heavy metals. • Climate change (N_2O), fresh water and marine eutrophication, and fossil fuel depletion. Particulate matter formation (NH_3 volatilization).	Dynamic Modelling (BioWin®) LCA (Umberto®) Ecoinvent database ReCiPe endpoint methods.	Urine source separation and enhanced primary clarification had positive effects on effluent quality and energy consumption. Nitritation coupled with Anammox for nitrogen removal from urine was identified as an interesting option. Hot spots needing further optimisation were also identified, including infrastructure, N_2O emissions, and heavy metals in sludge.

Table 4. *Cont.*

No	Reference/Citation/Source	Country/Region	Technology/Product	Stage	Environmental Concerns Highlighted	Method of Assessment/Indicators	Conclusions
7	Fang [76]/94/ Water Research	Denmark	A wastewater resources recovery technology under development is called TRENS. Water recovery used for fertigation (organic amendment)	Production and application.	**Impacts** • Human toxicity impact for algae land application, due to the concentrations of heavy metals (zinc and mercury). • Emissions increase for biogas production. **Benefits** • Fewer impacts than baseline • Reduction of N_2O emissions (global warming category). • Offset mineral fertiliser production. • Decrease in marine eutrophication.	LCA using the EASETECH model (DTU, Denmark). - Fourteen impact categories USETox to assess human toxicity.	Key findings include the reduction in impacts by up to 15% for global warming and 9% for marine eutrophication with the TRENS system. Its benefits are limited by the low demand for freshwater substitution and fertiliser. The LCA suggests areas for improvement in construction and operation impacts, contrary to conventional WWTPs focus. The assessment provided feedback to technology developers, highlighting areas for better characterisation and technology evaluation.
8	Sena [77]/93/Journal of Cleaner Production	USA	Precipitation of struvite from WWTP 1. Base case scenario 2. Full case (struvite recovery) 3. Struvite Recovery System Case (isolates struvite recovery system)	Production	• Slight decrease in environmental impact in most but not all of the considered impact categories due to the additional energy and resource demands for all categories except eutrophication	LCA (SimaPro 8.5.2.0 coupled with Ecoinvent 3.2) TRACI method midpoint impact factors: Ozone depletion, global warming, smog, acidification, eutrophication, carcinogenic, non-carcinogenic, respiratory effects, ecotoxicity, and fossil fuel depletion.	LCA shows that adding a struvite recovery system at Nine Springs WWTP generally improves the plant's environmental performance, although the independent impact of the struvite system is neutral. Future research should focus on reducing the environmental impacts of added chemicals, optimising nutrient recovery, and studying the effects of scale and transportation distances on environmental impacts. Recovering phosphorus and nitrogen as a valuable product can reduce the need to mine limited resources like phosphate rock.

Table 4. *Cont.*

No	Reference/Citation/Source	Country/Region	Technology/Product	Stage	Environmental Concerns Highlighted	Method of Assessment/Indicators	Conclusions
9	Vázquez-Rowe [60]/84/Waste Management	Belgium	Five different digestate treatment systems and a baseline scenario. 1. Baseline 2. Digestate drying and pelletizing 3. Digestate composting 4. Biological treatment, reverse osmosis and drying 5. Ammonia stripping and drying	Production, storage, and application.	**Impacts** • Climate change, particulate matter production and resource depletion • Resource depletion and emissions linked to climate change. **Benefits** • The treatment of raw digestate shows an overall environmental benefit when compared to the direct spreading of the digestate	LCA ReCiPe assessment method Final and midpoints MIXTRI 2.0 model [78].	Conversion technologies before spreading digestate on fields for fertilisation increased impacts such as global warming and energy use. However, this method has environmental benefits by reducing air emissions (ammonia), resulting in overall environmental gains compared to direct spreading. It is important to assess various impact categories to understand trade-offs between technologies and consider mitigating energy-related impacts by changing energy sources. Future research should focus on dynamic models to assess time-dependent processes and explore nutrient recovery from digestate, as well as conducting consequential LCA to evaluate the broader environmental implications of increased availability of digestate-derived fertilisers as substitutes for chemical fertilisers.
10	Prapaspongsa [64]/89/ Journal of Cleaner Production	Denmark	Twelve scenarios applying various treatment, storage and land application systems	Production and application	**Impacts** • Global warming • Aquatic eutrophication • Respiratory inorganics • Terrestrial eutrophication	LCA Consequential modelling Methods STEPWISE2006 IMPACT2002+ EDIP2003	The study suggests strategies including integrated treatment technology systems for energy and nutrient recovery and control of emissions at every handling stage. Anaerobic digestion-based scenarios are effective for reducing global warming, while incineration and thermal gasification-based scenarios are effective for minimising ammonia emissions and respiratory inorganics. Uncertainties in ammonia emissions from land application and storage systems were identified through sensitivity analyses.

While LCA is a well-established methodology for tracking the environmental impacts of BBFs throughout their life cycle, there is still no consensus on specific procedures and methodologies to ensure reliable and comparable results across studies [16]. Most studies favour the attributional LCA (ALCA) approach, which focuses on describing the environmental impacts directly associated with the production and use of a product or process within a defined system boundary. In contrast, the consequential LCA (CLCA) approach, which evaluates the broader environmental consequences of changes in demand or supply (i.e., such as policy shifts or market dynamics) is rarely applied. Among the ten most cited studies analysed, only one [65] employed the CLCA methodology. This limited use of CLCA highlights a gap in assessing the systemic implications of adopting BBFs at scale. Additionally, LCA studies have predominantly focused on process-oriented rather than product-oriented analyses, limiting the assessment of agronomic performance. Another important gap is the assessment of the multifunctionality provided by the BBFs (i.e., improving soil health, enhancing crop yield, and reducing environmental impacts), which can be solved using allocation or substitution methods or by combining other modelling approaches [79]. Finally, the deterministic nature of LCA analyses, which often rely on average values, with only a few studies incorporating uncertainty and sensitivity analyses and the inconsistency in life cycle impact assessment methods (e.g., ReCiPe, TRACI, CML, STEPWISE2006) further complicates the comparability of results, although international initiatives ILCD Handbook by the European Commission [80], the UNEP/SETAC Life Cycle Initiative, and the Product Environmental Footprint (PEF) framework are underway to harmonise these procedures.

4. Concluding Remarks

This study significantly contributes to the scientific community by highlighting the current research and scientific output on the sustainability performance of BBFs, particularly emphasising their environmental impacts, methods and hotspots.

The bibliometric analysis revealed two distinct periods of scientific output, with a sharp increase after 2016, led by research from Europe (Spain, Belgium, Italy, and Sweden) and North America (mainly the USA). Top authors and institutions reflected this geographical pattern and formed collaborative networks. Keyword trends shifted post-2018 from terms like "phosphorus" and "anaerobic digestion" to "life cycle assessment" (LCA), "nutrient recovery", and "resource recovery", indicating a move toward more holistic environmental evaluations. Publications were grouped into LCA-based and non-LCA studies. Both focused on nutrient recovery, especially phosphorus, from wastewater and livestock waste, with common techniques including struvite precipitation and anaerobic digestion. Non-LCA studies emphasised heavy metals, GHGs, and organic pollutants, often through direct measurements. LCA-based studies, by contrast, addressed broader impact categories (e.g., global warming, eutrophication, toxicity) but relied on average values, introducing greater uncertainty.

In both groups, the methodologies and indicators for assessing environmental impacts varied, making inter-comparability of results challenging. However, each approach offers distinct advantages. The non-LCA approach stands out in detailed measurements, such as specific experiments to quantify GHG emissions from BBFs, which can generate valuable datasets for future reference and LCA databases. It also focuses on environmental performance rather than a specific process and benefits from robust statistical and sampling methods. On the other hand, the LCA approach is notable for its ability to assess a product, system, or process throughout its entire life cycle (cradle-to-grave). It also offers a broad range of methods and indicators, some tailored to specific impacts, and the capacity to evaluate the multifunctionality of BBFs through allocation techniques. Unfortunately, there is still no methodological consensus or standardised guidelines for evaluating BBFs, making it challenging to obtain robust, reliable, and comparable results across studies.

Therefore, future research must be oriented toward the pursuit of creating a more comprehensive assessment framework. It is essential to explore alternative approaches, like non-LCA guidelines or commonly used indicators, that can complement the LCA approach—such as those found in existing EU Best Available Techniques (BAT) reference documents or sustainability certification schemes.

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