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A Bibliometric perspective on the evolution of research in sludge management: Opportunities and challenges

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Abstract

Conventionally regarded as a liability, sewage sludge (SS) continues to accumulate due to rapid industrialisation and global population growth. However, the conversion of SS into energy and nutrients presents a promising alternative for sustainable waste management. Drawing from the Web of Science database and using VOSviewer for bibliometric mapping, this review investigates the research trends, intellectual structure, and collaborative networks in sludge management over the past decade. It further evaluates the strengths, particularly in alignment with the Sustainable Development Goals (SDGs), as well as the weaknesses, opportunities, and threats associated with current sludge management practices. The analysis reveals that key emerging research themes include microbial diversity in activated sludge, biological treatment processes and their limitations, and thermochemical conversion for energy and nutrient recovery. Future research is encouraged to focus on innovative remediation approaches for emerging contaminants and microplastics, and the development of scalable technologies for the commercial production of energy, nutrients, and value-added chemical products from SS. This study offers a comprehensive overview of the evolution of sludge management research and provides critical insights to inform policy direction, investment priorities, and academic engagement. It also advocates for increased financial support, stakeholder incentives, and collaborative partnerships, noting that substantial progress toward achieving multiple SDGs can be made through strategic investment in sludge management initiatives.

Keywords: Bibliometric, Research trend, Sewage sludge, Sustainable development goals, SwoT analysis.

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1. Introduction

The world's population is growing exponentially, placing increasing stress on natural resources and putting them at risk of depletion in the near future [1]. This strain is further intensified by the rising energy demands of emerging economies, which lead to increased fossil fuel consumption and the release of large volumes of greenhouse gases into the atmosphere, thereby exacerbating climate change [2, 3]. These challenges have resulted in the search for alternative energy sources. One promising approach is the utilization of sewage sludge (SS).

Sludge is a semi-solid waste derived from the primary and secondary treatment of domestic and industrial wastewater delivered to the wastewater treatment plant by the sewerage system [4]. Traditionally, SS has been considered a liability, and the volume of municipal SS has continued to increase over the years due to the increased global population and rapid industrialization [1]. SS disposal remains a crucial point of discussion among the stakeholders [5]. Globally, over 70% of sludge is disposed via landfills and incineration [6]. The landfill requires massive landfill space, contributes to global warming, and represents a significant source of groundwater contamination [1]. On the other hand, incineration reduces sludge mass and volume by 70% and 90%, respectively [7]. However, the residues of incineration and air pollutants released during the incineration process form major sources of ecological degradation [8, 9]. Therefore, increasing concerns and stringent limitations on conventional sludge disposal practices have resulted in the shift of focus to the energy resource potential of SS [10].

The use of SS as a resource reduces the need for its storage and, at the same time, minimises the burden on the environment by reducing greenhouse gas emissions and other pollutants [4]. SS could be beneficially used for energy generation, pelletisation of sludge as fuel, fertilizer from pasteurized sludge, as an additive and fuel in fired bricks, and for co-combustion in coal-fired power stations [11]. However, the high pathogen and heavy metal levels in SS, besides the high generation rates, necessitate proper management of this waste. SS reuse, recycling, and disposal are managed in many countries via legislation systems based on requirements that vary across countries based on the financial capability, availability of land, population density, and social acceptance [12].

2. Literature Review

In recent decades, researchers across the globe have conducted extensive research on wastewater sewage sludge (WWSS) treatment and management. The vast publications may be overwhelming, making identifying the trend and knowledge gap in the WWSS management research field challenging. Hence, some systematic and bibliometric reviews have recently been conducted on the available research articles in the field. Zhang, et al. [13] summarised the available review papers on sludge treatments with much focus on emerging contaminants, as well as the thermal processes, mesophilic, and hyperthermophilic co-digestion of sludge. Nkuna, et al. [14] presented an overview of energy derivation from wastewater sludge, considering finance, technology, and socio-environmental factors. A review of the literature highlighting the demerits of the conventional methods of sludge treatment (aerobic and anaerobic) was conducted by Anjum, et al. [15]. The use of sludge pre-treatment technologies such as thermal, ultrasonic, microwave, Fenton, wet oxidation, and photocatalysis was recommended. Gherghel, et al. [16] provided an overview of the utilisation of wastewater sludge in energy and material recovery.

In recent years, bibliometric analysis has gained significant attention in environmental remediation and wastewater treatment, allowing for a more comprehensive understanding of research trends and advancements in these areas. A bibliometric analysis of the literature on aerobic granular sludge from 1997 to 2020 was conducted by Purba, et al. [17]. Hou, et al. [18] provided a bibliometric review of sludge dewatering research from 1993 to 2022. Although research in sewage sludge management (SSM) spans a wide range of disciplines, a systematic investigation of its strengths, weaknesses, opportunities, and threats (SWOT) has not yet been conducted. This study aims to fill this gap by analysing the output profiles and citation characteristics of SSM-related literature over the past decade. It examines the productivity of journals, authors, countries, and institutions contributing to the field. Furthermore, the intellectual structure and emerging trends in SSM research are explored. Finally, the study assesses the strengths, weaknesses, opportunities, and threats associated with current and future sludge management practices.

3. Methodology

The bibliometric data were collected using the Web of Science (WoS) Core Collection database. The WoS is a high-quality digital tool commonly employed to retrieve and evaluate different types of publications [19]. Previous researchers have claimed that WoS has a significant edge over other databases because it comprises high-quality journals with intensive editorial rigor and best practices [20, 21]. A comprehensive search of wastewater sludge management (SM) articles published between 2015 and 2024 was conducted on January 3, 2025 using the following search strategies (title, abstract, keywords) = ["sludge" AND ("recycl*" OR "reuse" OR "treatment" OR "reduc*" OR "management")]. A total of 16,509 publications on SM were identified in the WoS database. The literature type was filtered to "Article," and the language was restricted to English, resulting in 16,235 articles. Further screening based on the WoS categories was carried out. Articles in the WoS category that were not directly related to SM research, such as infectious diseases, pharmacology, pharmacy, veterinary sciences, and economics, were excluded. Finally, 12,666 valid publications were obtained and extracted from the WoS core collection database (Figure 1).

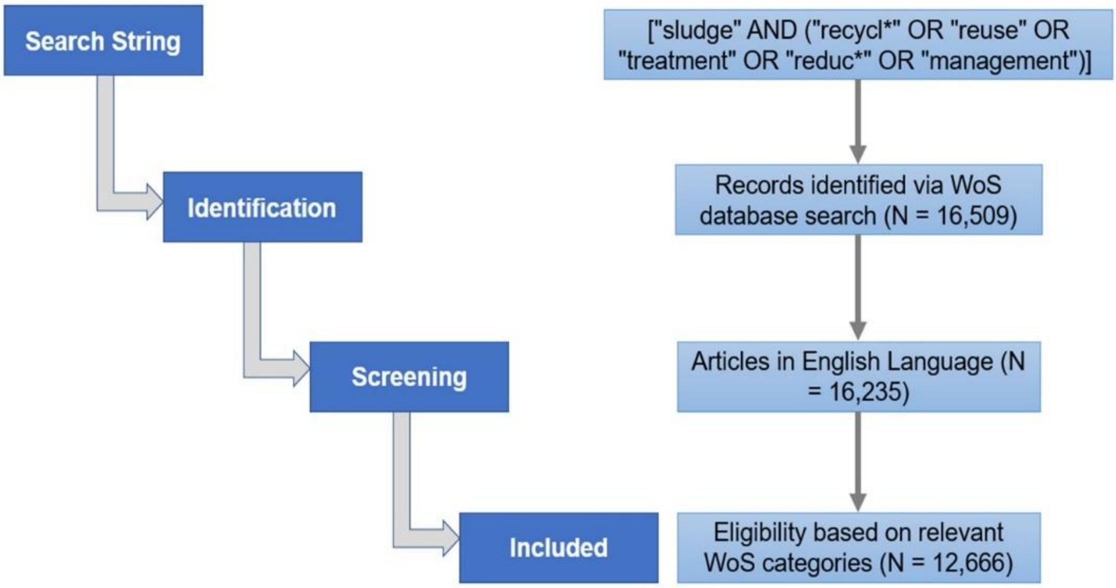

Figure 1.
PRISIMA diagram of the data mining for the bibliometric dataset.

The bibliometric and visualization analysis was conducted using VOSviewer (version 1.6.20). VOSviewer is a Java-based visualisation software tool developed by the Centre for Science and Technology Studies at Leiden University [22]. In this study, the VOSviewer was used to investigate the research trend, and intellectual and social structure of the SM research field. A systematic review of the SWOT analysis of sludge management was also conducted.

4. Results and Discussion

4.1. Descriptive Statistics

On screening the database collection from the WoS, a total of 12,666 publications, comprising journal articles only, were obtained. The publications in the dataset used for the study were published in 720 journals by 45,431 authors affiliated with 9071 organisations in 142 countries. The database collection has 343,551 cited references (Table 1).

Table 1.
Overview of the dataset used for the bibliometric analysis.

Description	Results
Timespan	2015:2024
Sources (Journals only)	720
Documents	12,666
Cited references	343,551
Average citations per doc	17.9
Keywords Plus (ID)	12,893
Author's Keywords (DE)	24,490
Authors	45,431
Countries	142
Organisations	9,071

4.2. Publication Trends in Sludge Management Research

Figure 2 presents the annual trends of publications in SM research in the last decade. An increase in published articles in SM research occurred from 2015 to 2016, followed by a slight drop in publication numbers in 2017. After this, there was a gradual rise in publication productivity from 2017 to 2022, where the optimum level of publications was observed. However, the last two years have experienced a slight decline in the publication rate. The study shows a strong linear relationship of 0.98 between the publication year (x) and the cumulative number of publications (y).

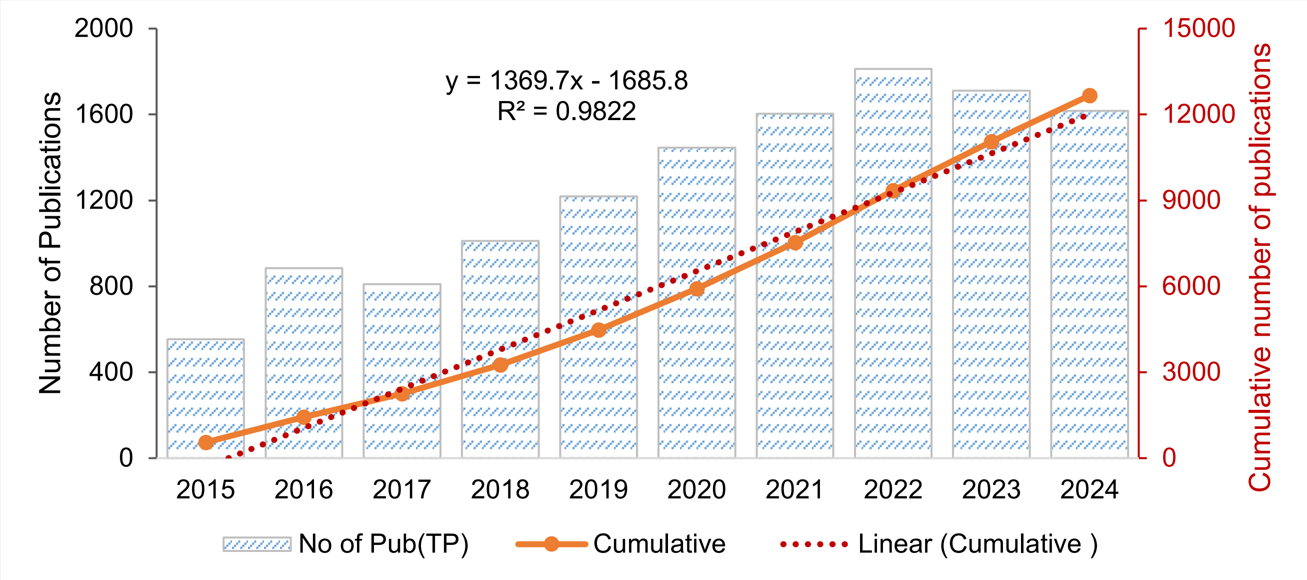

Figure 2.
Annual trends of publications in sludge management research.

Furthermore, the study showed that ≥97% of articles published between 2015 and 2021 had at least one citation, while the cited publications to total publication ratio declined to 94%, 85%, and 47% in 2022, 2023, and 2024, respectively (Table 2). In addition, a sharp increase in the total number of citations (TC) was observed from 2015 to 2016, followed by a slight increase from 2016 to 2017, and then a gradual rise till 2019. In 2019, the optimum TC level of 34,579 was achieved. This was followed by a sporadic drop from 30,157 in 2020 to 2,095 in 2024. García-Villar and García-Santos [23] argue that it is not uncommon for recently published articles to receive relatively fewer citations than older publications.

Table 2.
Summary of the annual productivity of the sludge management research dataset.

Year	Number of Publications (NP)	Cited Publications (NCP)	Total Citations (TC)	TC/NP	TC/NCP
2015	553	540	18,716	33.84448	34.65926
2016	884	867	28,204	31.90498	32.53057
2017	810	800	30,184	37.2642	37.73
2018	1012	1006	29,880	29.52569	29.70179
2019	1219	1194	34,579	28.36669	28.96064
2020	1445	1415	30,157	20.8699	21.31237
2021	1603	1556	25,948	16.18715	16.67609
2022	1812	1703	18,467	10.1915	10.84381
2023	1711	1449	8,608	5.030976	5.940649
2024	1617	752	2,095	1.295609	2.785904

4.3. Source Productivity and Influence

The study database comprises 12,666 articles published in 720 journals. To investigate the productivity of the sources with respect to SM research publications, the journals were grouped based on article production frequencies: 1, 2, 3-9, 10-50, 51-100, and >100 articles (Figure 3a). The study showed that 32% of the total journals, equivalent to 228 journals, published one article, whereas 15.3%, 27.6%, 18.8%, equivalent to 110, 199, and 135 journals published 2, 3-9, and 10-50 articles, respectively. On the other hand, only 18 and 30 journals, equivalent to 2.5% and 4.2% of the total journals, published 51-100 and >100 articles in SM research, respectively. This is not uncommon, as Lotka's law affirms that the number of authors or journals producing many publications declines with the increased frequency of articles published [21].

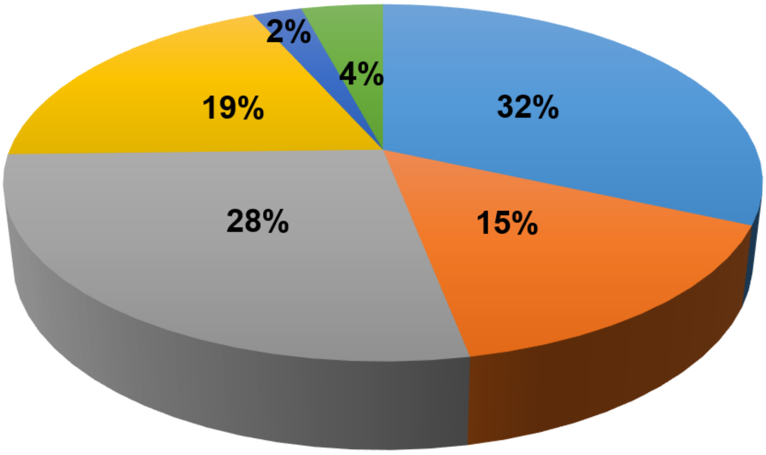

Figure 3a.
Productivity levels of all journals included in the sludge management research dataset.

Considering the publication in the SM research, Water Science and Technology took the lead with 679 articles, followed by Water and Sustainability Journals with 566 and 511 articles, respectively (Figure 3b). In 2015, the lowest productivity levels in SM research articles were reported in all the journals except Desalination and Water Treatment. Unlike most journals, which had fewer than 50 publications in 2015 and 2016, Desalination and Water Treatment had its peak production in these years, with 102 and 213 article publications, respectively. After 2016, consistently low SM article publications were observed in the Desalination and Water Treatment Journal till 2023, which could have resulted from a shift in journal preferences of authors in the SM research field. Water Science and Technology Journal was most productive in 2018 with 120 publications, whereas Water and Sustainability Journals peaked in 2023 and 2022 with 118 and 116 articles, respectively. The names and characteristics of the most productive journals in SM research are presented in Table 3. Several indices examine a sources or author's impact in a particular research field. These include publications' total citations (TC), h-index, g-index, and m-index [24, 25]. It is important to note that the higher these indices are for an author or source, the greater the influence and relevance of the author or source in the given field of study. Based on all these parameters, the Water Research Journal is the most impactful in the SM research field.

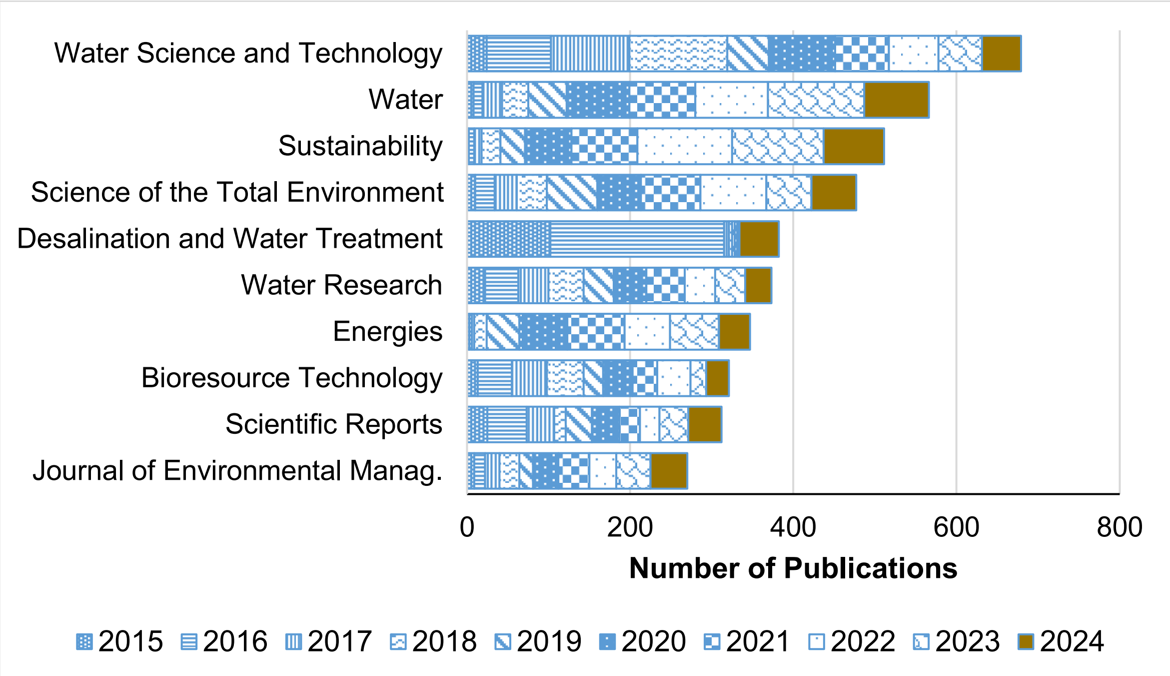

Figure 3b.
The productivity levels of the top ten Journals in the sludge management research field.

Table 3.
The 10 most influential journals in sludge management research based on the dataset used for analysis.

Journal name	TP	TP (rank)	Cited Pub	TC	TC (rank)	h-index	g-index	PY_Start	m-index
Water Science and Technology	679	1	611	6268	5	32	40	2015	3.6
Water	566	2	471	5178	10	32	45	2015	3.6
Sustainability	511	3	432	4703	11	32	46	2015	3.6
Science of the Total Environment	477	4	464	15612	2	61	98	2015	6.8
Desalination and Water Treatment	382	5	340	3011	14	22	30	2015	2.4
Water Research	373	6	363	19356	1	76	117	2015	8.4
Energies	347	7	320	3665	13	28	37	2015	3.1
Bioresource Technology	321	8	308	12083	3	62	84	2015	6.9
Scientific Reports	312	9	283	8694	4	49	78	2015	5.4
Journal of Environmental Management	270	10	243	5728	7	39	61	2015	4.3

4.4. The Geographical Participation and Collaboration of Countries in Sludge Management Research

For growth and transparency in SM-related research, there is a need for collaboration among authors and organisations within and outside any given country. This section discusses countries' contributions and collaborative efforts in developing SM research. One hundred forty-two countries were involved in SM-related research between 2015 and 2024 (Figure 4a). The participating countries are highlighted in blue on the map, while those in ash colour were not involved in SM research. It is important to note that the strength of the blue hue shows the level of country involvement in SM research; countries with a deeper hue of blue indicate countries with many publications in SM research, and vice versa. Factors such as NP, TC, Links, and Total link strength (TLS) were considered when investigating countries' contributions and collaborative significance. Link is the number of authors/organisations/countries (in this case) that an author/organisation/country is associated with in collaborative research. On the other hand, TLS is the total number of times an author/ organisation/ country is linked with others in collaborative research in the given field [22]. The higher the links and TLS, the stronger the connection. Table 4 presents the 20 most relevant countries in SM research. Findings from the study indicate China and the USA as the leading countries in SM-related research, with 3,319 and 1,209 publications, 61,030 and 32,128 citations, and TLS of 1,527 and 1,069, respectively. Considering the total publications in SM-related research and TC, Spain took the third position with 958 publications and 19,841 citations; however, using the TLS as a measure for countries' performance, the third position was shifted to England.

Figure 4b showcases a co-authorship network of countries, illustrating the cooperation between countries involved in SM research. Using 10 publications per country as the threshold, 90 countries met this criterion. Based on international collaborations with ≥10 publications in SM research, the collaborative network indicated the USA as the most prominent country, having collaborated with 75 countries. In contrast, China, England, Spain, and Australia collaborated with 73, 71, 64, and 53 other countries, respectively. Countries within the same colour-coded clusters suggest a higher degree of collaboration among them. Larger nodes represent highly productive countries in terms of publication strength. The line between two nodes connotes the association between the countries, with thicker lines connoting a stronger link between the countries.

Table 4.
The 20 most influential countries in sludge management-related research.

Country	TP	Rank (NP)	TC	Links	Total Link Strength (TLS)	Rank (TLS)
China	3319	1	61030	86	1527	1
USA	1209	2	32128	89	1069	2
Spain	958	3	19841	71	617	5
Poland	843	4	11485	57	290	16
England	662	5	18439	78	840	3
Italy	633	6	12686	74	499	8
Australia	504	7	14535	56	626	4
Germany	500	8	11814	79	539	7
Japan	486	9	7703	64	437	11
Netherlands	481	10	17798	67	540	6
India	448	11	7534	72	429	12
France	411	12	9409	71	440	10
Brazil	404	13	5726	54	248	17
Canada	400	14	6300	59	394	13
Denmark	391	15	13417	58	458	9
South Korea	350	16	5540	49	301	15
Sweden	343	17	8552	65	373	14
Iran	257	18	4243	45	145	20
Portugal	242	19	3764	41	212	18
South Africa	236	20	2345	51	172	19

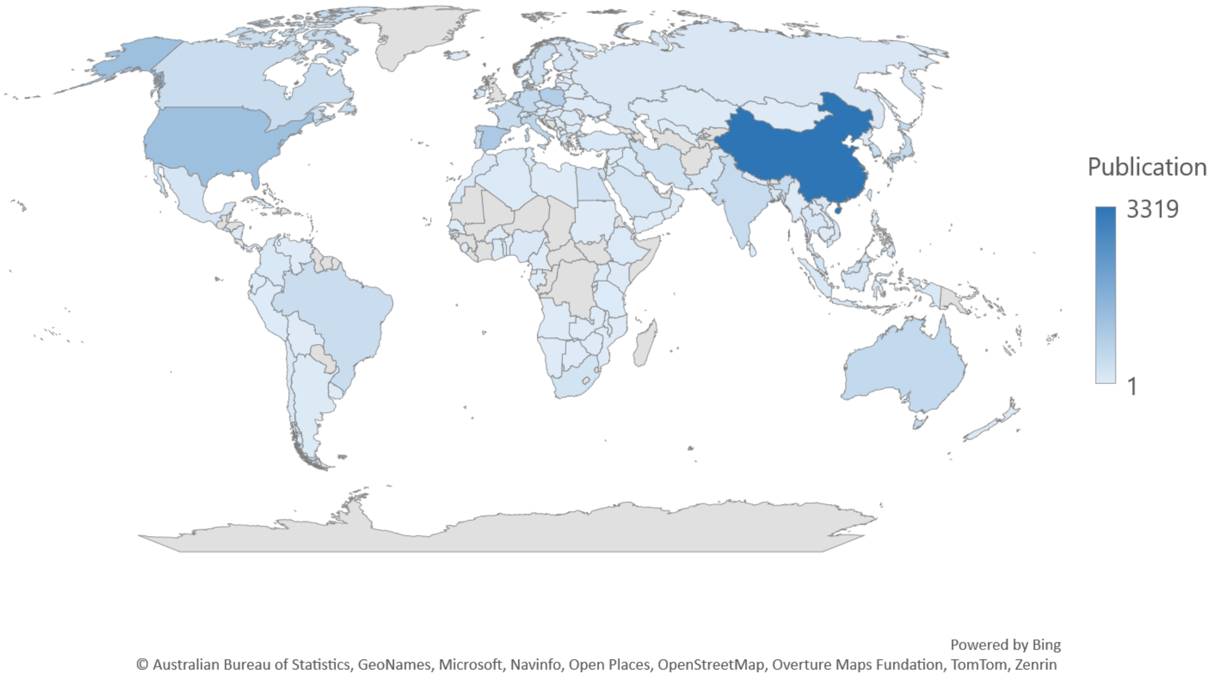

Figure 4a.
Geographical distribution of sludge management research based on scientific publication.

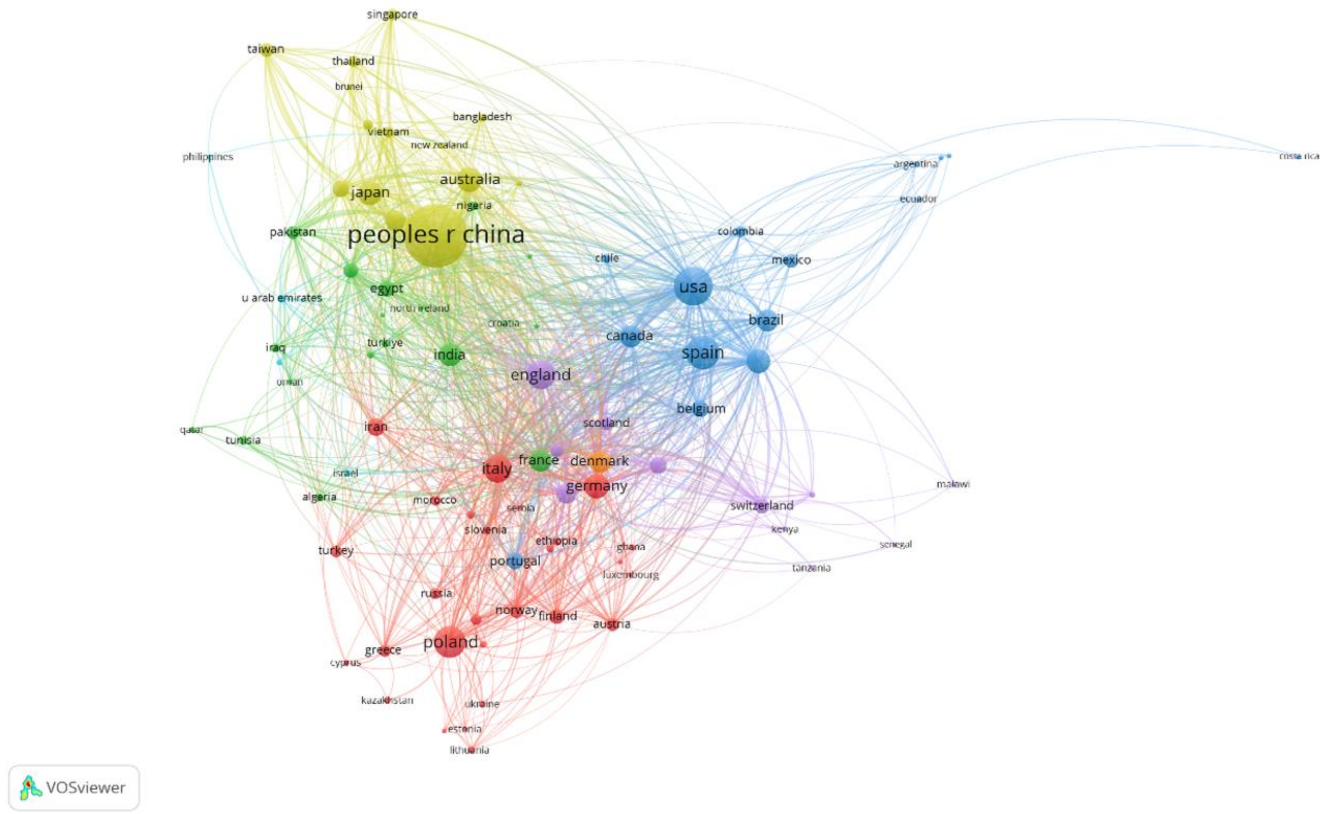

Figure 4b.
Co-authorship network of countries with at least 10 publications in sludge management research.

4.5. Productivity and Collaboration among Organisations in SM research

In most cases, the significance of an organisation/ author/country in a field of study is often measured by the number of publications. However, to foster scientific growth and development and transparency in research, there is a need for collaboration. VOSviewer was used to assess the co-authorship network of 9,071 organisations involved in SM research in the last decade. A network of 999 organisations grouped into 7 clusters was involved in SM collaborative research (Figure 5a). The organisations are represented with nodes, and node sizes depend on the number of published articles. The lines between the nodes signify the research collaborations between the organisations, with thicker lines representing stronger collaborations. Table 5 presents the thirteen most productive organisations in SM-related research. The five most relevant universities are the Chinese Academy of Science, Delft University of Technology, the Technical University of Denmark, Harbin Institute of Technology, and Tongji University. Notably, all the academic institutions included in the list of the best-publishing organisations still fall within the top twelve collaborative organisations in SM research, except the University of Warmia and Mazury (highlighted in yellow). The University of Warmia and Mazury was displaced to the 37th position based on its collaborative strength.

Table 5.
The most productive organisations in sludge management-related research.

Academic Institution	Country	NP	NP Rank	TC	Link	TLS	TLS Rank	Citations per doc
Chinese Academy of Science	China	337	1	9638	253	648	1	28.6
Delft University of Technology	Netherlands	219	2	6841	131	285	3	31.2
Technical University of Denmark	Denmark	187	3	6886	130	278	5	36.8
Harbin Institute of Technology	China	170	4	3837	88	189	7	22.6
Tongji University	China	145	5	3731	96	181	8	25.7
University Chinese Academy of Science	China	138	6	3753	104	291	2	27.2
University of Technology Sydney	Australia	137	7	6243	100	285	4	45.6
University of Warmia and Mazury	Poland	117	8	1933	22	72	37	16.5
University of Ghent	Belgium	114	9	2301	110	181	9	20.2
Tsinghua University	China	111	10	2872	111	192	6	25.9
Aalborg University	Denmark	104	11	5099	86	141	12	49.0
University of Queensland	Australia	101	12	2813	98	175	10	27.9
Tohoku University		85	13	1665	51	146	11	19.6

Furthermore, a co-authorship network analysis of the organisation with at least 50 publications was conducted, which yielded a network of 7 clusters comprised of 49 organisations, with cumulative links and TLS of 261 and 845, respectively (Figure 5b). The network showed that the Chinese Academy of Science was the most influential and had the strongest collaborative link regarding SM research with the University of the Chinese Academy of Science.

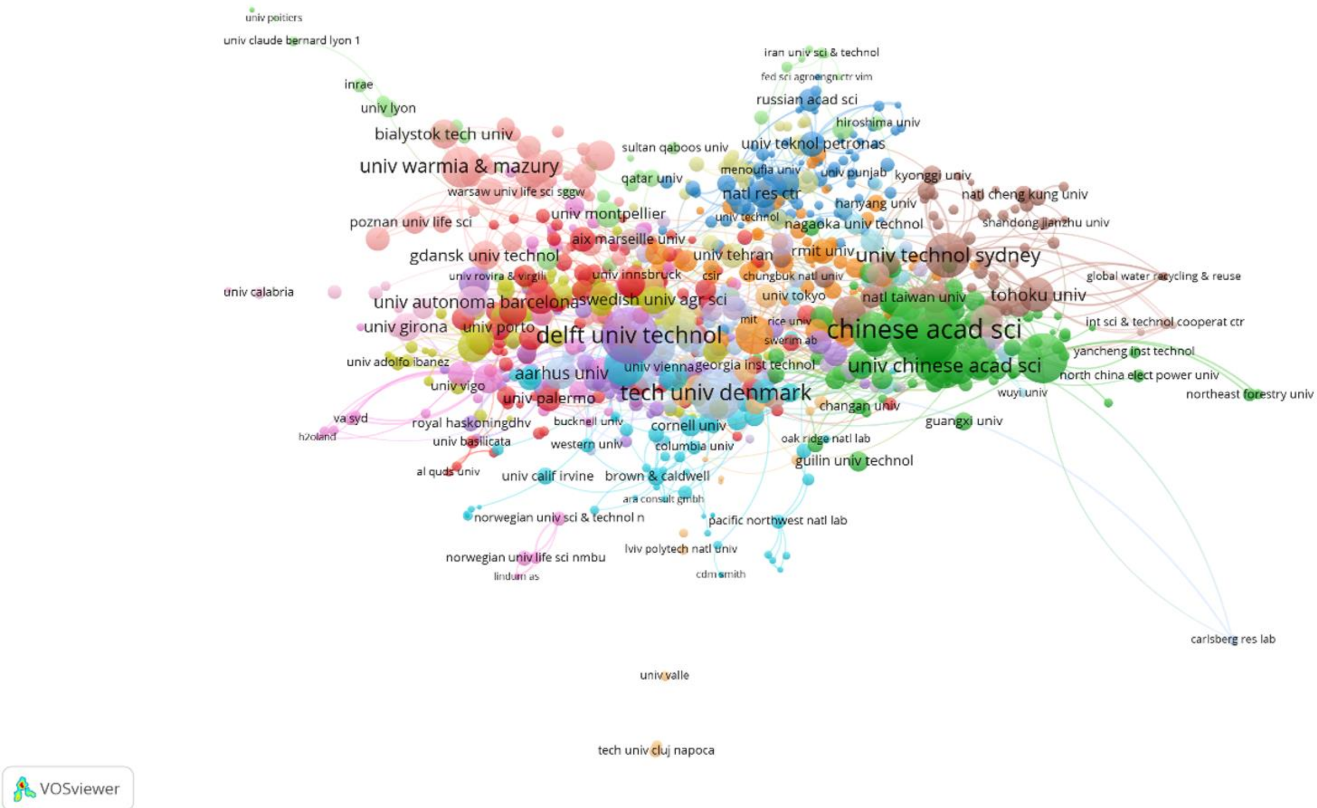

Figure 5a.
Collaborative network of all academic institutions involved in sludge management-related research.

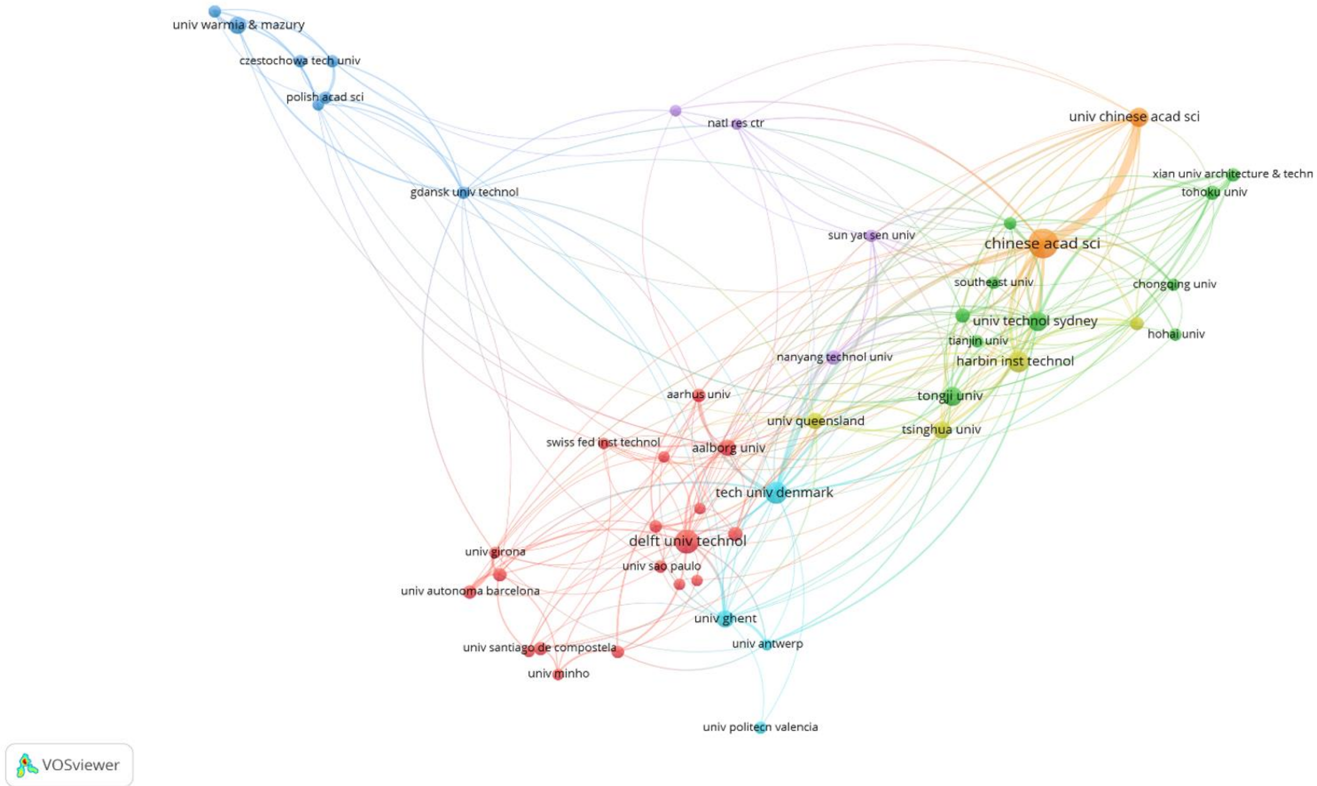

Figure 5b.
Collaborative network of academic institutions with at least 50 publications in sludge management-related research.

4.6. Intellectual Structure of Sludge Management

Bibliographic coupling was used to investigate the intellectual structure of research in SM. Bibliographic coupling is a science mapping technique used for analysing the connections between citing publications to understand the current or periodic evolution of themes in a field of study [26]. This technique operates on the assumption that two papers with comparable references are also similar in content. Bibliographic coupling functions by grouping publications into thematic clusters according to shared references. In contrast to co-citation analysis, bibliographic coupling allows for the visibility of recent and niche publications since the generated thematic clusters are based on the citing publications [27]. Bibliographic coupling analysis of the publications with a threshold of 50 citations in the study resulted in a bibliographic network of 1,044 items grouped into 9 clusters (Figure 6). The colour of an item is determined by the cluster to which the item belongs. In other words, items within the same cluster have the same colour [22]. Each item in a cluster denotes a publication represented with a node whose size is influenced by the number of citations received. Publications with closely related concepts are grouped in the same cluster. Invariably, the coloured clusters present the various themes in SM research. Table 6 shows three representative studies from each cluster and the associated theme.

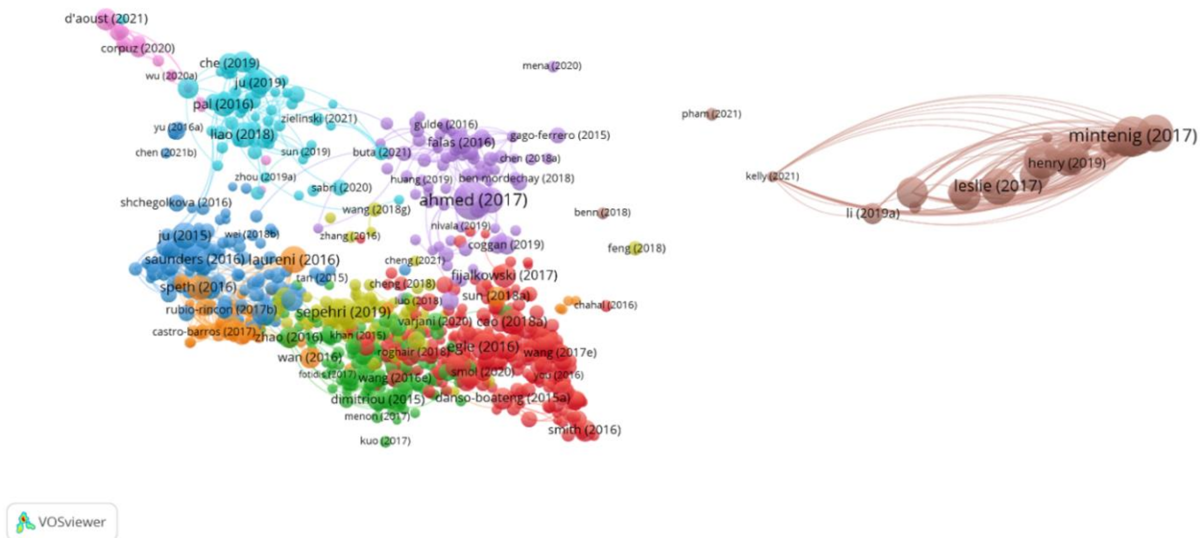

Figure 6.
Document bibliographic coupling.

Table 6.
Three representative studies from the clusters in the bibliographic coupling.

Cluster	Authors	Title of publications	Journal	Theme (Summary of the publications in the cluster)
Pink	D'Aoust, et al. [28]	Quantitative analysis of SARS-Cov-2 RNA from wastewater solids in communities with low COVID-19 incidence and prevalence	Water Research	Quantification of viruses and SARS-Cov-2 in wastewater and sewage
	Michael-Kordatou, et al. [29]	Sewage analysis as a tool for the COVID-19 pandemic response and management: the urgent need for optimised protocols for SARS-Cov-2 detection and qualification	J Environ Chem Eng	
	Corpuz, et al. [30]	Viruses in wastewater: occurrence, abundance and detection methods	SciTotEnv	
Sky blue	Pal, et al. [31]	The structure and diversity of human, animal and environmental resistomes	Microbiome	The sources, structure, and diversity of resistomes in the environment
	Ju, et al. [32]	Wastewater treatment plant resistomes are shaped by bacterial composition, genetic exchange, and upregulated expression in the effluent microbiomes	Isme Journal	
	Vikesland, et al. [33]	Toward a comprehensive strategy to mitigate dissemination of environmental sources of antibiotic resistance	Env. Sci & Tech.	
Deep Blue	Ju and Zhang [34]	Bacterial assembly and temporal dynamics in activated sludge of a full-scale municipal wastewater treatment plant	Isme Journal	Microbial communities in activated sludge
	Guo, et al. [35]	Dissecting microbial community structure and methane-producing pathways of a full-scale anaerobic reactor digesting activated sludge from wastewater treatment by metagenomic sequencing	Microbial cell factories	
	Saunders, et al. [36]	The activated sludge ecosystem contains a core community of abundant organisms	Isme Journal	
Orange	Laureni, et al. [37]	Mainstream partial nitritation and anammox: long-term process stability and effluent quality at low temperatures	Water research	Nitrogen removal in wastewater treatment system via nitritation and anammox
	Li, et al. [38]	Nitrogen removal by granular nitritation-anammox in an up-flow membrane-aerated biofilm reactor	Water research	
	Speth, et al. [39]	Genome-based microbial ecology of anammox granules in a full-scale wastewater treatment system	Nature communications	
Green	Zhao, et al. [40]	Potential enhancement of direct interspecies electron transfer for syntrophic metabolism of propionate and butyrate with biochar in up-flow anaerobic sludge blanket reactors	Bioresource Tech	Anaerobic sludge as a potential source of fuel
	Dimitriou, et al. [41]	Carbon dioxide utilisation for	Energy &	

		production of transport fuels: process and economic analysis	Environmental Science	
	Salvador, et al. [42]	Carbon nanotubes accelerate methane production in pure cultures of methanogens and in a syntrophic coculture	Environmental Microbiology	
Red	Egle, et al. [43]	Phosphorus recovery from municipal wastewater: an integrated comparative technological, environmental and economic assessment of phosphorus recovery technologies	Science of Total Environment	Phosphorus recovery from municipal wastewater
	Wang, et al. [44]	Electrochemically mediated precipitation of phosphate minerals for phosphorus removal and recovery: progress and perspective	Water research	
	Garfí, et al. [45]	Life cycle assessment of wastewater treatment systems for small communities: activated sludge, constructed wetlands and high-rate algal ponds	Journal of cleaner production	
Purple	Verlicchi and Zambello [46]	Pharmaceuticals and personal care products in untreated and treated sewage sludge: occurrence and environmental risk in the case of application on soil – a critical review	Science of the Total Environment	The occurrence, environmental risk and removal of micropollutants and emerging contaminants from wastewater sludge
	Ahmed, et al. [47]	Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: a critical review	Journal of hazardous materials	
	Falås, et al. [48]	Tracing the limits of organic micropollutant removal in biological wastewater treatment	Water research	
Lemon	Sepehri and Sarrafzadeh [49]	Activity enhancement of ammonia-oxidizing bacteria and nitrite-oxidizing bacteria in activated sludge process: metabolite reduction and CO_2 mitigation intensification process	Applied water science	The role of bacteria in metabolite reduction
	Felz, et al. [50]	Chemical characterisation methods for the analysis of structural extracellular polymeric substances	Water research	
	Milferstedt, et al. [51]	The importance of filamentous cyabacterian the development of oxygenic photogranules	Scientific Reports	
Brown	Leslie, et al. [52]	Microplastic en route: field measurements in the dutch river delta and Amsterdam canals, wastewater treatment plants, north sea sediments and biota	Environment International	Identification and measurement of microplastic in effluent and WWTP sludge
	Mintenig, et al. [53]	Identification of microplastic in effluents of wastewater treatment plants using focal plane array-based micro-fourier-transform infrared imaging	Water research	
	Li, et al. [54]	Enhancement in adsorption potential of microplastics in sewage sludge for metal	Water research	

		pollutants after the wastewater treatment process		

The academic links between the clusters are also interesting. The deep blue cluster focuses on the structure of microbial communities in activated sludge. The closest cluster to it is the orange cluster, which emphasises the removal of Nitrogen in wastewater via nitritation and anammox. These two research themes are interrelated. Microbes play a significant role in the nitritation-anammox process, especially ammonia-oxidizing bacteria, which convert ammonia to nitrite (nitritation), and anaerobic ammonia-oxidizing bacteria, which convert nitrite and ammonia into nitrogen gas (anammox reaction) [55]. Maintaining a balanced population of these microbes is essential for effective nitrogen removal in wastewater treatment systems. In addition, the lemon, green, and red clusters are interspersed, indicating interconnectivity among the three clusters. The lemon cluster focuses on "the role of bacteria in metabolite reduction". In contrast, the green and red clusters deal with the themes "Anaerobic sludge as a potential fuel source" and "Phosphorus recovery from municipal wastewater". These three research topics are related. Anaerobic sludge is rich in organic content and serves a dual purpose: energy generation and nutrient recycling. In anaerobic digestion processes, bacteria play a key role in organic matter decomposition, producing metabolites like methane (biogas) and volatile fatty acids [56]. The efficiency of biogas production is influenced by the ability of the microbial community to reduce complex metabolites into simpler ones like methane. The residual sludge from anaerobic digestion still contains nutrients, including phosphorus, which can be recovered [57].

Overall, the research focuses on essential subjects such as energy generation and nutrient recovery from anaerobic sludge, the occurrence, environmental risk, and removal of emerging contaminants, which include pharmaceuticals, microplastics, personal care products, and antibiotics, the monitoring of viruses and SARS-Cov-2 in sewage sludge and sources, structure and diversity of resistomes in the ecosystem.

4.7. Research Evolution in Sludge Management

This section deals with the trends of research themes/topics in the SM domain over the past ten years. The study employed the keyword co-occurrence analysis to investigate the research directions. Keyword co-occurrence analysis operates on the assumption that two keywords are somewhat connected when they frequently occur together. The approach enables us to analyse shifts in research fronts and themes in a given field by determining the frequency of keyword pairs that appear in the scientific topic of interest [22]. The thematic evolution in SM research was assessed using the keyword Overlay Visualization in VOS viewer (Figure 7). Each keyword is represented by a node with a size dependent on its frequency. The colours of the nodes range from blue to green, then yellow, spanning from years before 2019 to years after 2021. The keywords in blue represent themes that gained popularity before 2020 (phase 1), while those in green represent commonly discussed topics among scholars in SM research from 2020 to 2021 (phase 2). However, the terminologies in yellow colour represent the current themes in SM research (phase 3). The research trends illustrated by the top 15 authors' keywords used in each phase are presented in Table 7. Phase 1 dealt with the degradation of sewage sludge using the biological approach, microbial biodiversity of activated sludge, and their associated challenges, such as heavy metal toxicity and inhibition of microbial growth. However, SM research in the second phase entails anaerobic digestion of sludge. In phase 3, resource recovery, which involves energy generation and nutrient recovery in SS using thermochemical technologies such as pyrolysis, carbonisation, co-pyrolysis, incineration, hydrothermal liquefaction, and co-combustion, was mainly discussed by the authors.

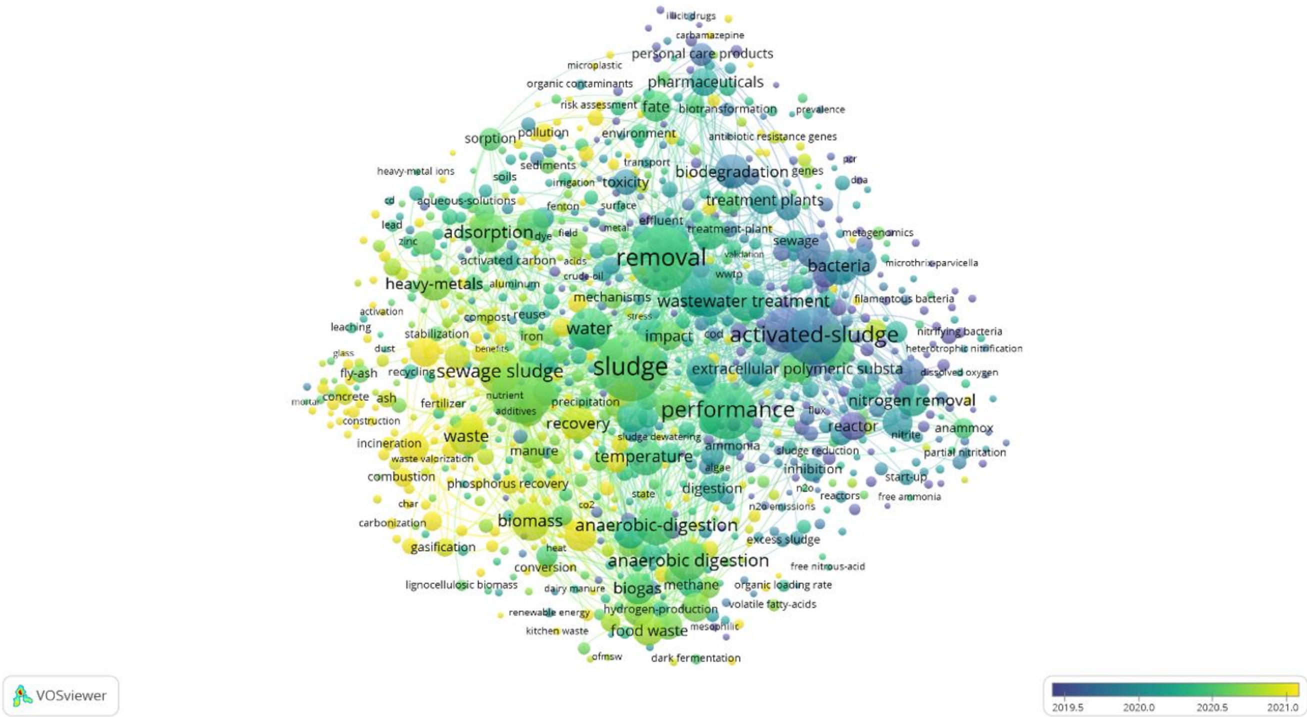

Figure 7.
The evolution of themes in the sludge management research field over time.

Table 7.
Evolution of research in sludge management from 2015 to 2024.

Phase 1: 2015-2020				**Phase 2: 2020-2021**			
Keyword	**Frequency**	**Rank**	**APY**	**Keyword**	**Frequency**	**Rank**	**APY**
Activated-sludge	1554	1	2019.8	Sludge	2124	1	2020.5
Waste-water treatment	996	2	2019.6	Removal	1983	2	2020.4
Bacteria	582	3	2019.9	Sewage-Sludge	1781	3	2020.6
Biodegradation	561	4	2019.8	Performance	1497	4	2020.4
Activated sludge	543	5	2019.7	Waste-water	1331	5	2020.2
Denitrification	434	6	2020.0	Water	815	6	2020.4
Diversity	408	7	2019.9	Degradation	812	7	2020.2
Reactor	377	8	2019.5	Anaerobic digestion	743	8	2020.5
Nitrification	359	9	2019.7	Anaerobic-digestion	713	9	2020.5
System	358	10	2020.0	Adsorption	711	10	2020.6
Toxicity	319	11	2019.9	Wastewater treatment	668	11	2020.3
Identification	298	12	2019.9	Biomass	665	12	2020.9
Membrane bioreactor	287	13	2019.5	Waste	621	13	2020.9
Inhibition	261	14	2020.0	Microbial community	601	14	2020.5
Model	258	15	2020.0	Temperature	589	15	2020.4
Keyword	Frequency	Rank	APY	Keyword	Frequency	Rank	APY
Biochar	435	1	2021.4	Hydrochar	123	9	2021.2
Pyrolysis	413	2	2021.1	Hydrogen	119	10	2021.1
Circular economy	248	3	2022.0	Life cycle assessment	117	11	2021.2
Resource recovery	194	4	2021.1	Particles	105	12	2021.2
Hydrothermal carbonization	173	5	2021.4	Nutrient recovery	100	13	2021.1
Mechanism	171	6	2021.2	Wastewater treatment plants	93	14	2021.1
Waste management	128	7	2021.2	Incineration	91	15	2021.1
Microplastics	126	8	2022.2				

Where APY is the average publishing year

4.8. SWOT Analysis

A SWOT analysis is a framework that examines the internal and external environments of a project in order to identify its core competencies/strengths, weaknesses, opportunities, and threats [58]. For proper running of sludge management in any community/nation, it is essential that such a setting maximises its strengths, minimises its weaknesses and threats, and takes advantage of the opportunities. The strengths, weaknesses, opportunities, and threats associated with sludge management are presented below:

4.8.1. Strengths of Sludge Management and Their Alignment with the SDGs

The utilization of sewage sludge (SS) for energy production offers numerous environmental and economic benefits. It significantly reduces the SS storage, transportation, and disposal burden, lowering greenhouse gas and other pollutant emissions. Moreover, it mitigates risks associated with SS storage, such as the leaching of nutrients and heavy metals, eutrophication, and contamination of water bodies [4]. These benefits contribute directly to the achievement of several Sustainable Development Goals (SDGs), including SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water).

In addition, applying treated sludge on agricultural soils improves soil physicochemical properties by enriching them with nitrogen, phosphorus, and other micronutrients. This practice promotes nutrient recycling within the ecosystem, enhances the food chain, and supports the lives of organisms in the ecological system. It aligns with SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land). By nourishing the soil, crop productivity is improved, which leads to increased job creation and boosts the gross domestic product (GDP). Consequently, it supports the realization of SDG 8 (Decent Work and Economic Growth), as well as SDG 1 (No Poverty), SDG 2 (Zero Hunger), and SDG 3 (Good Health and Well-being).

Furthermore, sludge stabilized with lime and fly ash has demonstrated biocidal potency due to the generation of ammonia (NH_3) gas. When applied to soils, this reduces the need for synthetic pesticides, thereby enhancing crop yield and agricultural sustainability [59]. This approach contributes to SDG 1 and SDG 2 (No Poverty and Zero Hunger), improves societal well-being (SDG 3), reduces economic inequalities (SDG 10), conserves life on land (SDG 15), and promotes sustainable urban development (SDG 11).

SS also plays a key role in renewable energy production through biogas generation, which can supplement electricity use, particularly in communities near biogas plants. This provides a sustainable energy solution for rural areas with limited access to electricity. Additionally, electricity generated from SS can be used to operate WW treatment plants, thus reducing their operational costs [10]. Replacing fossil fuels with biogas as an energy source minimises greenhouse gas emissions. SS can also be co-combusted with coal and other fuels in power plants, further cutting emissions. These waste-to-energy innovations support the goals of SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 13 (Climate Action), and SDG 11 (Sustainable Cities and Communities).

Moreover, biochar derived from sewage sludge has proven valuable in environmental remediation. Its rich mesoporous and microporous structure makes it a suitable adsorbent for wastewater treatment, a soil amendment, and a sustainable ingredient in the production of modified cement and concrete composites [60]. It can also serve as a fuel or fuel supplement in power generation.

Clean energy production from SS, such as hydrogen fuel produced via thermochemical combustion, has the potential to serve as an alternative automotive fuel [56]. The partial or complete substitution of fossil fuels with hydrogen supports SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

Additionally, thermochemical processes can convert SS into valuable chemical products such as adhesives, epoxy resins, bio-polyols, and polyurethane foams [61]. These products contribute to industrial development and economic growth, aligning with SDG 8 (Decent Work and Economic Growth). In conclusion, adopting cost-effective and locally appropriate technologies in sludge management ensures long-term sustainability and practical applicability across diverse settings.

4.8.2. Weaknesses

Despite the increasing recognition of SS as a resource, several critical challenges hinder the effectiveness and widespread adoption of sustainable management practices. A significant drawback lies in the high capital investment required to set up advanced treatment systems and their substantial operational and maintenance costs [4]. These financial demands often make it difficult for developing countries and smaller municipalities to implement or sustain such technologies. Moreover, the biological treatment of SS, though widely practiced, is often accompanied by the emission of offensive odours, which negatively impact surrounding communities and raise environmental and public health concerns [55].

Additionally, the successful deployment of many SS treatment and conversion technologies depends heavily on specialized technical knowledge, which is not readily available in many regions. Most advanced SS conversion systems remain either underdeveloped or in pilot stages in various countries, making commercial-scale implementation a persistent hurdle [1]. Further complicating the scenario is the presence of contaminants such as heavy metals, pathogens, emerging contaminants (ECs), and even more hazardous EC intermediates in treated sludge and its end-products. These pose significant health and ecological risks, especially when such by-products are applied to land. Efforts like bioaugmentation, which involve the use of specific microbial strains, often face challenges in maintaining microbial viability and activity after application [62-64]. In addition, emission control remains a significant issue in thermochemical processes like pyrolysis, gasification, and incineration, as these methods can release harmful substances if not properly managed [4]. Collectively, these weaknesses limit the reliability, safety, and scalability of current sludge management approaches

4.8.3. Opportunities

SS management presents a wide range of socio-economic and environmental opportunities, particularly when circular economy principles are applied. The recycling and reusing of sludge materials can stimulate job creation across various sectors, including waste collection, treatment, transportation, and the production of value-added products. These income-generating ventures collectively contribute to national economic advancement and have the potential to improve a country's gross domestic product significantly. Additionally, SS management offers environmental opportunities through carbon sequestration. The thermochemical transformation of sludge to biochar and application of treated sludge to soil lock carbon in the biochar and soil matrix, respectively. Replacing conventional fossil fuels with bio-gas derived from sludge conversion can reduce greenhouse gas emissions and support national climate targets.

From a development perspective, sludge management innovations in low-income countries can attract investment and funding through initiatives such as the Clean Development Mechanism, which provides financial incentives for emission reduction projects. Each unit of greenhouse gas avoided through these initiatives can be translated into tradable carbon credits, creating further economic value [65]. Moreover, with adequate funding, incentives from the government, stakeholders' partnership, and policy support, SS research can become a platform for adopting global best practices, stimulating innovation, and fostering public engagement. Educational campaigns and community involvement are key to ensuring that sludge management strategies are locally relevant and widely accepted, ultimately encouraging collaboration and sustainable implementation.

4.8.4. Threats

Sewage sludge (SS) management faces several pressing threats that could undermine its long-term viability and sustainability. One primary concern is the gradual disappearance of traditional treatment techniques, which, although outdated, have historically served as accessible options for low-resource settings [4]. At the same time, the regulatory landscape surrounding sludge management is becoming increasingly complex and dynamic, making it difficult for many operators to consistently meet evolving standards and secure the necessary permits for operation. This challenge is further compounded by the technical complexity of newer, more sustainable treatment technologies, which demand a high level of expertise that is not always readily available. In addition, the significant financial investment required to establish and maintain these advanced systems can deter adoption, particularly in developing regions. In conclusion, public resistance, especially concerning the land application of treated sludge, continues to pose a barrier to widespread acceptance and implementation, mainly due to health, safety, and environmental concerns [10].

5. Conclusion

5.1. Implication

Findings from the study indicate China and the USA are the leading countries in SM-related research. South Africa is the only African country in the top 20 countries in SM research, suggesting that Africa is lagging in SM research; therefore, more efforts need to be put in place by the SM stakeholders to bring about improvement and sustainability. The review also revealed diversity and the roles of microbial communities in SS waste-energy conversion, biological degradation of SS, and the thermochemical conversion of SS to energy and nutrients as the major research trends among researchers in the SM field in the last decade (2015-2024). The review has also linked the strength of SM projects to the SDGs, indicating that most of the SDGs could be achieved if SM research is prioritized.

5.2. Limitations

This research is restricted to documents indexed in the WOS database, such that publications not indexed could not be analysed; the limitations of the WoS database may also apply to this study. Secondly, there could be inherent bias in some aspects of the study that call for the researchers' discretion, such as the inclusion of articles into the dataset based on relevant WoS categories and assigning threshold values to items in VOSviewer, which could have added a degree of ambiguity to the analysis. Furthermore, the database created for the study covers 2015 to 2024. As innovation evolves, we expect new topics, ideas, and approaches to be introduced, significantly changing the study's conclusions. Future studies should be conducted using several databases to understand the dynamics of the field and new study fields.

5.3. Future Research

Further research on the bioremediation of ECs and the commercial production of end-products from the advanced methods of SS waste-to-energy conversion techniques is recommended. Public awareness campaigns should also be conducted, and public involvement in SM-related projects should be encouraged to foster a sustainable environment.

References

[1] S. R. Naqvi *et al.*, "Recent developments on sewage sludge pyrolysis and its kinetics: Resources recovery, thermogravimetric platforms, and innovative prospects," *Computers & Chemical Engineering,* vol. 150, p. 107325, 2021. https://doi.org/10.1016/j.compchemeng.2021.107325

[2] M. Nadal, M. Schuhmacher, and J. L. Domingo, "Cost–benefit analysis of using sewage sludge as alternative fuel in a cement plant: A case study," *Environmental Science and Pollution Research,* vol. 16, no. 3, pp. 322-328, 2009. https://doi.org/10.1007/s11356-008-0063-7
[3] A. C. M. Loy *et al.*, "Thermogravimetric kinetic modelling of in-situ catalytic pyrolytic conversion of rice husk to bioenergy using rice hull ash catalyst," *Bioresource Technology,* vol. 261, pp. 213-222, 2018. https://doi.org/10.1016/j.biortech.2018.04.020
[4] A. Grobelak *et al.*, "Environmental impacts and contaminants management in sewage sludge-to-energy and fertilizer technologies: Current trends and future directions," *Energies,* vol. 17, no. 19, p. 4983, 2024. https://doi.org/10.3390/en17194983
[5] O. o. S. Djandja, Z.-C. Wang, F. Wang, Y.-P. Xu, and P.-G. Duan, "Pyrolysis of municipal sewage sludge for biofuel production: A review," *Industrial & Engineering Chemistry Research,* vol. 59, no. 39, pp. 16939-16956, 2020. https://doi.org/10.1021/acs.iecr.0c01546
[6] R. R. Z. Tarpani, C. Alfonsín, A. Hospido, and A. Azapagic, "Life cycle environmental impacts of sewage sludge treatment methods for resource recovery considering ecotoxicity of heavy metals and pharmaceutical and personal care products," *Journal of Environmental Management,* vol. 260, p. 109643, 2020. https://doi.org/10.1016/j.jenvman.2019.109643
[7] A. Elmi, A. a. Al-Khaldy, and M. AlOlayan, "Sewage sludge land application: Balancing act between agronomic benefits and environmental concerns," *Journal of Cleaner Production,* vol. 250, p. 119512, 2020. https://doi.org/10.1016/j.jclepro.2019.119512
[8] A. Abuşoğlu, E. Özahi, A. İ. Kutlar, and H. Al-jaf, "Life cycle assessment (LCA) of digested sewage sludge incineration for heat and power production," *Journal of Cleaner Production,* vol. 142, no. Part 4, pp. 1684-1692, 2017. https://doi.org/10.1016/j.jclepro.2016.11.121
[9] C. J. Lynn, R. K. Dhir, and G. S. Ghataora, "Environmental impacts of sewage sludge ash in construction: Leaching assessment," *Resources, Conservation and Recycling,* vol. 136, pp. 306-314, 2018. https://doi.org/10.1016/j.resconrec.2018.04.029
[10] S. Heimersson, M. Svanström, C. Cederberg, and G. Peters, "Improved life cycle modelling of benefits from sewage sludge anaerobic digestion and land application," *Resources, Conservation and Recycling,* vol. 122, pp. 126-134, 2017. https://doi.org/10.1016/j.resconrec.2017.01.016
[11] L. H. Lötter and A. R. Pitman, "Report to the water research commission on aspects of sewage sludge handling and disposal," WRC Report No. 316/1/97 Johannesburg City Council Wastewater and Scientific Services Departments, 1997.
[12] E. Wiśniowska, A. Grobelak, P. Kokot, and M. Kacprzak, *Sludge legislation-comparison between different countries. In Industrial and Municipal Sludge: Emerging Concerns and Scope for Resource Recovery*. Elsevier. https://doi.org/10.1016/B978-0-12-815907-1.00010-6, 2019.
[13] Q. Zhang, J. Hu, D.-J. Lee, Y. Chang, and Y.-J. Lee, "Sludge treatment: Current research trends," *Bioresource Technology,* vol. 243, pp. 1159-1172, 2017. https://doi.org/10.1016/j.biortech.2017.07.070
[14] S. G. Nkuna, T. O. Olwal, S. D. Chowdhury, and J. M. Ndambuki, "A review of wastewater sludge-to-energy generation focused on thermochemical technologies: An improved technological, economical and socio-environmental aspect," *Cleaner Waste Systems,* vol. 7, p. 100130, 2024. https://doi.org/10.1016/j.clwas.2024.100130
[15] M. Anjum, N. H. Al-Makishah, and M. Barakat, "Wastewater sludge stabilization using pre-treatment methods," *Process Safety and Environmental Protection,* vol. 102, pp. 615-632, 2016. https://doi.org/10.1016/j.psep.2016.05.022
[16] A. Gherghel, C. Teodosiu, and S. De Gisi, "A review on wastewater sludge valorisation and its challenges in the context of circular economy," *Journal of Cleaner Production,* vol. 228, pp. 244-263, 2019. https://doi.org/10.1016/j.jclepro.2019.04.240
[17] L. D. A. Purba *et al.*, "Discovering future research trends of aerobic granular sludge using bibliometric approach," *Journal of Environmental Management,* vol. 303, p. 114150, 2022. https://doi.org/10.1016/j.jenvman.2021.114150
[18] F. Hou, J. Zhang, L. Gan, H. Pang, G. Zhai, and W. Qiao, "A bibliometric review of sludge dewatering research from 1993 to 2022," *Desalination and Water Treatment,* vol. 315, pp. 342-354, 2023. https://doi.org/10.5004/dwt.2023.30140
[19] X. Ding, "Knowledge mapping of platform research: A visual analysis using VOSviewer," vol. 22, no. 3, pp. 454-463, 2020. https://doi.org/10.1007/S10660-020-09410-7
[20] Clarivate, "Web of science master journal list (WoS MJL)," Retrieved: https://mjl.clarivate.com/home. 2025. [Online]. Available: https://mjl.clarivate.com/home
[21] M. Aria and C. Cuccurullo, "bibliometrix: An R-tool for comprehensive science mapping analysis," *Journal of Informetrics,* vol. 11, no. 4, pp. 959-975, 2017. https://doi.org/10.1016/j.joi.2017.08.007
[22] N. J. Van Eck and L. Waltman, *VOSviewer manual*. Leiden, The Netherlands: Universiteit Leiden, 2023.
[23] C. García-Villar and J. García-Santos, "Bibliometric indicators to evaluate scientific activity," *Radiología (English Edition),* vol. 63, no. 3, pp. 228-235, 2021. https://doi.org/10.1016/j.rxeng.2021.01.002
[24] J. E. Hirsch, "An index to quantify an individual's scientific research output," *Proceedings of the National Academy of Sciences,* vol. 102, no. 46, pp. 16569-16572, 2005. https://doi.org/10.1073/pnas.0507655102
[25] L. Egghe, "Theory and practise of the g-index," *Scientometrics,* vol. 69, no. 1, pp. 131–152, 2006. https://doi.org/10.1007/s11192-006-0144-7
[26] I. Passas, "Bibliometric analysis: The main steps," *Encyclopedia,* vol. 4, no. 2, pp. 1014-1025, 2024. https://doi.org/10.3390/encyclopedia4020065
[27] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. M. Lim, "How to conduct a bibliometric analysis: An overview and guidelines," *Journal of Business Research,* vol. 133, pp. 285-296, 2021. https://doi.org/10.1016/j.jbusres.2021.04.070
[28] P. M. D'Aoust *et al.*, "Quantitative analysis of SARS-CoV-2 RNA from wastewater solids in communities with low COVID-19 incidence and prevalence," *Water Research,* vol. 188, p. 116560, 2021. https://doi.org/10.1016/j.watres.2020.116560
[29] I. Michael-Kordatou, P. Karaolia, and D. Fatta-Kassinos, "Sewage analysis as a tool for the COVID-19 pandemic response and management: The urgent need for optimised protocols for SARS-CoV-2 detection and quantification," *Journal of Environmental Chemical Engineering,* vol. 8, no. 5, p. 104306, 2020. https://doi.org/10.1016/j.jece.2020.104306
[30] M. V. A. Corpuz *et al.*, "Viruses in wastewater: Occurrence, abundance and detection methods," *Science of the Total Environment,* vol. 745, p. 140910, 2020. https://doi.org/10.1016/j.scitotenv.2020.140910

[31] C. Pal, J. Bengtsson-Palme, E. Kristiansson, and D. J. Larsson, "The structure and diversity of human, animal and environmental resistomes," *Microbiome,* vol. 4, no. 1, p. 54, 2016. https://doi.org/10.1186/s40168-016-0199-5

[32] F. Ju *et al.*, "Wastewater treatment plant resistomes are shaped by bacterial composition, genetic exchange, and upregulated expression in the effluent microbiomes," *The ISME Journal,* vol. 13, no. 2, pp. 346-360, 2019. https://doi.org/10.1038/s41396-018-0277-8

[33] P. J. Vikesland *et al.*, "Toward a comprehensive strategy to mitigate dissemination of environmental sources of antibiotic resistance," *Environmental Science & Technology,* vol. 51, no. 22, pp. 13061–13069, 2017. https://doi.org/10.1021/acs.est.7b03623

[34] F. Ju and T. Zhang, "Bacterial assembly and temporal dynamics in activated sludge of a full-scale municipal wastewater treatment plant," *The ISME Journal,* vol. 9, no. 3, pp. 683-695, 2015. https://doi.org/10.1038/ismej.2014.162

[35] J. Guo, Y. Peng, B.-J. Ni, X. Han, L. Fan, and Z. Yuan, "Dissecting microbial community structure and methane-producing pathways of a full-scale anaerobic reactor digesting activated sludge from wastewater treatment by metagenomic sequencing," *Microbial Cell Factories,* vol. 14, no. 1, p. 33, 2015. https://doi.org/10.1186/s12934-015-0218-4

[36] A. M. Saunders, M. Albertsen, J. Vollertsen, and P. H. Nielsen, "The activated sludge ecosystem contains a core community of abundant organisms," *The ISME Journal,* vol. 10, no. 1, pp. 11-20, 2016. https://doi.org/10.1038/ismej.2015.117

[37] M. Laureni *et al.*, "Mainstream partial nitritation and anammox: Long-term process stability and effluent quality at low temperatures," *Water Research,* vol. 101, pp. 628-639, 2016. https://doi.org/10.1016/j.watres.2016.05.005

[38] X. Li, S. Sun, B. D. Badgley, S. Sung, H. Zhang, and Z. He, "Nitrogen removal by granular nitritation–anammox in an upflow membrane-aerated biofilm reactor," *Water Research,* vol. 94, pp. 23-31, 2016. https://doi.org/10.1016/j.watres.2016.02.031

[39] D. R. Speth, M. H. in't Zandt, S. Guerrero-Cruz, B. E. Dutilh, and M. S. Jetten, "Genome-based microbial ecology of anammox granules in a full-scale wastewater treatment system," *Nature Communications,* vol. 7, no. 1, p. 11172, 2016. https://doi.org/10.1038/ncomms11172

[40] Z. Zhao *et al.*, "Potential enhancement of direct interspecies electron transfer for syntrophic metabolism of propionate and butyrate with biochar in up-flow anaerobic sludge blanket reactors," *Bioresource Technology,* vol. 209, pp. 148-156, 2016. https://doi.org/10.1016/j.biortech.2016.03.005

[41] I. Dimitriou, P. García-Gutiérrez, R. H. Elder, R. M. Cuéllar-Franca, A. Azapagic, and R. W. Allen, "Carbon dioxide utilisation for production of transport fuels: process and economic analysis," *Energy & Environmental Science,* vol. 8, no. 6, pp. 1775-1789, 2015. https://doi.org/10.1039/C4EE04117H

[42] A. F. Salvador *et al.*, "Carbon nanotubes accelerate methane production in pure cultures of methanogens and in a syntrophic coculture," *Environmental Microbiology,* vol. 19, no. 7, pp. 2727-2739, 2017. https://doi.org/10.1111/1462-2920.13774

[43] L. Egle, H. Rechberger, J. Krampe, and M. Zessner, "Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies," *Science of the Total Environment,* vol. 571, pp. 522-542, 2016. https://doi.org/10.1016/j.scitotenv.2016.07.019

[44] Y. Wang, P. Kuntke, M. Saakes, R. D. van der Weijden, C. J. Buisman, and Y. Lei, "Electrochemically mediated precipitation of phosphate minerals for phosphorus removal and recovery: Progress and perspective," *Water Research,* vol. 209, p. 117891, 2022. https://doi.org/10.1016/j.watres.2021.117891

[45] M. Garfí, L. Flores, and I. Ferrer, "Life cycle assessment of wastewater treatment systems for small communities: Activated sludge, constructed wetlands and high rate algal ponds," *Journal of Cleaner Production,* vol. 161, pp. 211-219, 2017. https://doi.org/10.1016/j.jclepro.2017.05.116

[46] P. Verlicchi and E. Zambello, "Pharmaceuticals and personal care products in untreated and treated sewage sludge: Occurrence and environmental risk in the case of application on soil—A critical review," *Science of the Total Environment,* vol. 538, pp. 750-767, 2015. https://doi.org/10.1016/j.scitotenv.2015.08.108

[47] M. B. Ahmed, J. L. Zhou, H. H. Ngo, W. Guo, N. S. Thomaidis, and J. Xu, "Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: A critical review," *Journal of Hazardous Materials,* vol. 323, pp. 274-298, 2017. https://doi.org/10.1016/j.jhazmat.2016.04.045

[48] P. Falås, A. Wick, S. Castronovo, J. Habermacher, T. A. Ternes, and A. Joss, "Tracing the limits of organic micropollutant removal in biological wastewater treatment," *Water Research,* vol. 95, pp. 240-249, 2016. https://doi.org/10.1016/j.watres.2016.03.009

[49] A. Sepehri and M.-H. Sarrafzadeh, "Activity enhancement of ammonia-oxidizing bacteria and nitrite-oxidizing bacteria in activated sludge process: metabolite reduction and CO2 mitigation intensification process," *Applied Water Science,* vol. 9, no. 5, p. 131, 2019. https://doi.org/10.1007/s13201-019-1017-6

[50] S. Felz, P. Vermeulen, M. C. van Loosdrecht, and Y. M. Lin, "Chemical characterization methods for the analysis of structural extracellular polymeric substances (EPS)," *Water Research,* vol. 157, pp. 201-208, 2019. https://doi.org/10.1016/j.watres.2019.03.068

[51] K. Milferstedt *et al.*, "The importance of filamentous cyanobacteria in the development of oxygenic photogranules," *Scientific Reports,* vol. 7, no. 1, pp. 1-15, 2017. https://doi.org/10.1038/s41598-017-16614-9

[52] H. Leslie, S. Brandsma, M. Van Velzen, and A. Vethaak, "Microplastics en route: Field measurements in the Dutch river delta and Amsterdam canals, wastewater treatment plants, North Sea sediments and biota," *Environment International,* vol. 101, pp. 133-142, 2017. https://doi.org/10.1016/j.envint.2017.01.018

[53] S. M. Mintenig, I. Int-Veen, M. G. Löder, S. Primpke, and G. Gerdts, "Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging," *Water Research,* vol. 108, pp. 365-372, 2017. https://doi.org/10.1016/j.watres.2016.11.015

[54] X. Li *et al.*, "Enhancement in adsorption potential of microplastics in sewage sludge for metal pollutants after the wastewater treatment process," *Water Research,* vol. 157, pp. 228-237, 2019. https://doi.org/10.1016/j.watres.2019.03.069

[55] S. Nanda and F. Berruti, "A technical review of bioenergy and resource recovery from municipal solid waste," *Journal of Hazardous Materials,* vol. 403, p. 123970, 2021. https://doi.org/10.1016/j.jhazmat.2020.123970

[56] A. K. Singh *et al.*, "Sustainable utilization of biowaste resources for biogas production to meet rural bioenergy requirements," *Energies,* vol. 16, no. 14, p. 5409, 2023. https://doi.org/10.3390/en16145409

[57] M. U. B. Khawer *et al.*, "Anaerobic digestion of sewage sludge for biogas & biohydrogen production: State-of-the-art trends and prospects," *Fuel,* vol. 329, p. 125416, 2022. https://doi.org/10.1016/j.fuel.2022.125416

[58] T. E. Aniyikaiye, J. N. Edokpayi, J. O. Odiyo, and S. J. Piketh, "Traditional brick making, environmental and socio-economic impacts: A case study of Vhembe District, South Africa," *Sustainability,* vol. 13, no. 19, p. 10659, 2021. https://doi.org/10.3390/su131910659

[59] E. Hadas, U. Mingelgrin, and P. Fine, "Economic cost–benefit analysis for the agricultural use of sewage sludge treated with lime and fly ash," *International Journal of Coal Science & Technology,* vol. 8, no. 5, pp. 1099-1107, 2021. https://doi.org/10.1007/s40789-021-00439-z

[60] N. K. Soni, K. Yadav, and P. V. Bhale, "Synthesis and characterization of sewage sludge biochar toward adsorptive removal of pollutants for sustainability: A review," *Journal of Thermal Analysis and Calorimetry,* vol. 150, pp. 3967–3989, 2025. https://doi.org/10.1007/s10973-025-14065-3

[61] M. Ganesapillai *et al.*, "Waste to energy: A review of biochar production with emphasis on mathematical modelling and its applications," *Heliyon,* vol. 9, no. 4, p. e14873, 2023. https://doi.org/10.1016/J.HELIYON.2023.E14873

[62] S. Sharma, S. Basu, N. P. Shetti, M. N. Nadagouda, and T. M. Aminabhavi, "Microplastics in the environment: Occurrence, perils, and eradication," *Chemical Engineering Journal,* vol. 408, p. 127317, 2021. https://doi.org/10.1016/j.cej.2020.127317

[63] S. Xu, J. Yao, M. Ainiwaer, Y. Hong, and Y. Zhang, "Analysis of bacterial community structure of activated sludge from wastewater treatment plants in winter," *BioMed Research International,* vol. 2018, no. 1, p. 8278970, 2018. https://doi.org/10.1155/2018/8278970

[64] M. Dubey, S. Mohapatra, V. K. Tyagi, S. Suthar, and A. A. Kazmi, "Occurrence, fate, and persistence of emerging micropollutants in sewage sludge treatment," *Environmental Pollution,* vol. 273, p. 116515, 2021. https://doi.org/10.1016/j.envpol.2021.116515

[65] S. Olaleru, J. Kirui, F. Elegbeleye, and T. Aniyikaiye, "Green technology solution to global climate change mitigation," *Energy, Environment and Storage,* vol. 1, no. 1, pp. 15–28, 2021.