Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.30140

315 (2023) 342–354
December

A bibliometric review of sludge dewatering research from 1993 to 2022

Feng Hou[a,b], Jinghui Zhang[a,b,*], Lili Gan[a,b], Hongtao Pang[a,b], Guoguang Zhai[a,b], Weiping Qiao[a,b]

[a]*Xinkai Environment Investment Co., Ltd., Beijing 101199, China, Tel.: +86-13488745920; email: jhzhang06@126.com (J. Zhang), Tel.: +86-010-56862600; email: houfengtougao@126.com (F. Hou), Tel.: +86-17601666565; email: ganlilitougao@126.com (L. Gan), Tel.: +86-13466727341; email: panghongtaotougao@126.com (H. Pang), Tel.: +86-17601666830; email: zhaiguoguangtougao@126.com (G. Zhai), Tel.: +86-13811696301; email: qiaoweipingtougao@126.com (W. Qiao)*
[b]*China Water Environment Group Co., Ltd., 7/F, block A, Wanda Plaza, Xinhua West Street, Beijing 101101, China*

Received 11 July 2023; Accepted 8 November 2023

ABSTRACT

The process of wastewater treatment generates significant volumes of sludge, typically characterized by high water content. The practice of sludge dewatering plays a crucial role in reducing the volume of sludge and consequently, the associated costs of subsequent treatment, transportation, and disposal. This paper provides an exhaustive and impartial summary of research trends in sludge dewatering, spanning the period from 1993 to 2022. The bibliometric data utilized in this study were sourced from the Web of Science Core Collection database. Over 30 y, 5,836 papers have been published on sludge dewatering, witnessing a rapid growth trend in the number of published papers. The highest contributions in terms of the number of papers were made by authors hailing from China, followed by authors from the USA, Canada, Australia, and Japan. An analysis of keywords indicated that anaerobic digestion was the most frequently used. Three prominent research hotspots emerged: the impact of extracellular polymeric substances on sludge dewatering; the role of thermal hydrolysis in enhancing sludge anaerobic digestion; and the dual aspects of hydrothermal carbonization and heavy metals recovery in the context of sludge reuse and disposal.

Keywords: Sludge dewatering; Bibliometrics; Hotspot analysis.

1. Introduction

Sewage treatment plants generate vast volumes of sludge, typically composed of over 90% water. It is estimated that sludge treatment accounts for approximately 30%–60% of the operational costs incurred by a wastewater treatment plant [1,2]. Sludge dewatering is a critical step in the sludge treatment process, serving to reduce the volume of sludge, and by extension, the costs of sludge transportation and disposal. Sludge, being generally difficult to dewater, exhibits varying degrees of dewatering effectiveness, contingent on the source of sewage and the employed treatment processes [3]. With the application of a decanter centrifuge or belt filter, the water content of sludge can be brought down to 70%–80%, while a plate and frame filter press can dewater sludge to less than 60% water content. Prior research primarily explored factors influencing sludge dewatering and developed diverse practical strategies to enhance the sludge dewatering process [4].

Bibliometrics, an interdisciplinary science, leverages mathematical and statistical methods to conduct quantitative analyses of all knowledge carriers. It serves to identify research trends and hotspots [5]. Recently, an increasing number of bibliometric studies have been undertaken to examine hotspots and prospective research across various fields. These include trends in health risks and the impact

* Corresponding author.

of heavy metals on human health [6], wastewater treatment and emerging pollutants [7], and anaerobic digestion technology [8]. Such studies offer novel insights to policymakers and researchers and assist in identifying directions for future research and policy formulation [9]. However, to date, bibliometric studies focusing on sludge dewatering technology are few. Bibliometric software is extensively utilized for the creation and graphical representation of bibliometric networks. In this study, bibliometric tools, namely VOSviewer and CiteSpace, were employed to analyze the data of sludge dewatering papers published between 1993 and 2022. Areas of analysis encompassed major subject categories, principal institutions and researchers, and research hotspots and trends. The data summaries presented here aim to offer researchers a more comprehensive and detailed understanding of the field of sludge dewatering.

2. Methods

2.1. Data collection

The foundation for this bibliometric study is the data collected from the globally recognized Web of Science (WoS) database, a well-established platform representing the breadth and depth of worldwide scientific research. A key segment of this platform, the WoS Core Collection database, comprises citation data for the most influential scientific journals and international conferences. This component was selected as the data source for this study. A comprehensive search was conducted on 2023-04-23 for literature published from 1993–2022, employing the following search strategies (title, abstract, keywords) = ((sewage sludge OR sludge) AND (de-water OR dewater OR de-hydrate OR dehydrate OR dewatering OR dewaterability OR dehydration)). This search of the WoS Core Collection database yielded 5,836 papers.

2.2. Data analysis

Bibliometric software is instrumental in the visualization and graphic representation of research activities within a specific field, facilitating the identification of research hotspots and trends [7]. In this study, CiteSpace (version 6.1.R2) and VOSviewer (version 1.6.17) software were used to conduct a bibliometric analysis of sludge dewatering. This analysis relied on document information retrieved from WoS with the aim of identifying the most influential papers, authors, research themes, and trends over time within the sludge dewatering field. Furthermore, collaboration networks were clearly and concisely visualized. Impact factor values were obtained from the 2022 Journal Citation Reports.

3. Results and discussion

3.1. Summary of scientific papers

Data from the 5,836 publications selected from the WoS Core Collection database, published from 1993 to 2022, were used for our analysis (Fig. 1). These publications were found in 1,060 journals, spanning 14 subfields, and were authored by 13,078 contributors from 3,523 institutions across 102 countries.

3.2. Temporal distribution of papers

Fig. 2 illustrates the number of sludge dewatering publications produced annually from 1993 to 2022. The annual count of publications gradually increased over the period, surpassing 200 only in 2013. From 2013 to 2022, the annual number of publications witnessed a sharp rise, from 213 to 479. The year 2021 saw the most publications, totaling 506, indicating a growing interest in sludge dewatering research. The substantial increase in the number of publications post-2013 correlates with the growth in research on deep sludge dewatering methods and technologies [10–12].

3.3. Statistical analysis of subject categories and journals

The publications spanned 126 subject categories, as represented in Table 1. As some publications were assigned to multiple subject categories, the cumulative percentage exceeds 100%. This overlap in percentages arises from the fact that certain publications can be classified under more than one subject category when considering total distribution. The subject category with the highest number of published papers was Environmental Sciences, accounting for 50.48%

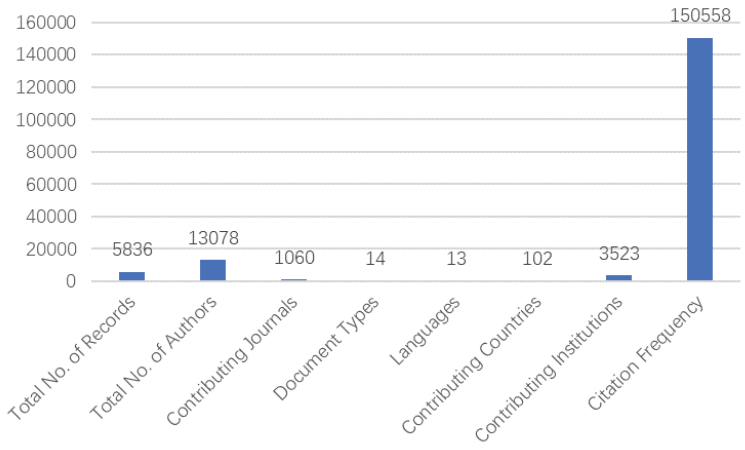


Fig. 1. Summary of the selected data categories used in the study.

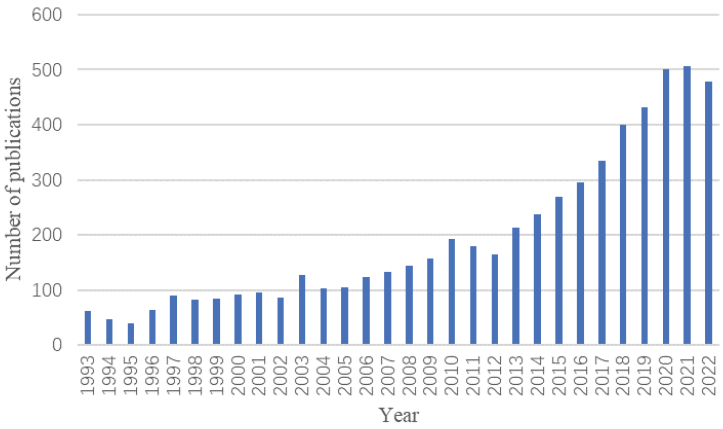


Fig. 2. Number of publications published annually in 1993–2022.

Table 1
The ten subject categories with the most published papers

Subject categories	Publications	Percentage (%)
Environmental Sciences	2,946	50.48
Engineering Environmental	2,185	37.44
Water Resources	1,381	23.66
Engineering Chemical	1,180	20.22
Energy Fuels	623	10.68
Biotechnology Applied Microbiology	494	8.47
Agricultural Engineering	314	5.38
Chemistry Multidisciplinary	242	4.15
Green Sustainable Science Technology	211	3.62
Materials Science Multidisciplinary	159	2.72

of the total. Following this, Environmental Engineering comprised 37.44%, Water Resources contributed 23.66%, Chemical Engineering at 20.22%, Energy Fuels at 10.68%, Applied Microbiology and Biotechnology at 8.47%, Agricultural Engineering at 5.38%, Multidisciplinary Chemistry at 4.15%, Green Sustainable Science Technology at 3.62%, and Multidisciplinary Materials Science at 2.72%. This distribution of subject categories indicates that the majority of the papers have an environmental focus.

To better understand the citation patterns across various disciplines, a dual-map analysis was utilized to examine the characteristics of the publication portfolios [13]. Fig. 3 presents a dual-map overlay visualization, created using CiteSpace software, depicting the citation tracks. The disciplines of the citing journals are portrayed on the left side, while those of the cited journals are shown on the right side, linked by curves. The majority of the citing journals fall within the domain of "veterinary, animal science", with the cited journals mainly representing the fields of "chemistry, materials, physics" and "environmental, toxicology, nutrition".

By analyzing the distribution of journals, we can pinpoint the major journals in the realm of sludge dewatering from 1993 to 2022. Table 2 displays the top 10 most prolific journals, determined by the number of relevant articles published in the sludge dewatering field, along with the number and percentage of sludge dewatering-related papers in each journal, and their respective impact factor (IF).

Water Science and Technology was the most productive journal, accounting for 7.75% of all the papers. It was followed by Water Research (6.34%), Bioresource Technology

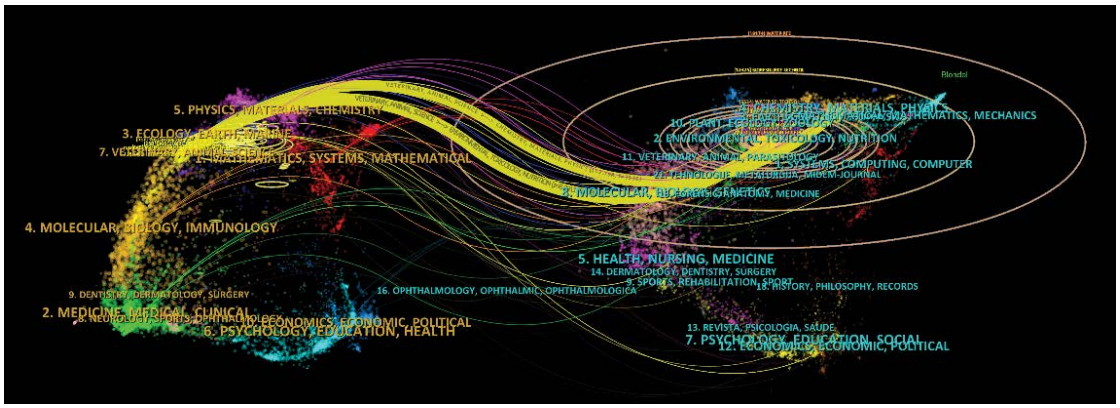


Fig. 3. Dual-map overlay of sludge dewatering research.

Table 2
Top 10 most productive journals from 1993 to 2022

Journal	Publications	Percentage (%)	IF (2022)
Water Science and Technology	452	7.75	2.43
Water Research	370	6.34	13.4
Bioresource Technology	274	4.7	11.889
Science of the Total Environment	183	3.14	10.753
Chemical Engineering Journal	161	2.76	16.744
Journal of Environmental Management	148	2.54	8.91
Chemosphere	130	2.23	8.943
Desalination and Water Treatment	123	2.11	1.273
Environmental Technology	119	2.04	3.306
Water Environment Research	118	2.02	3.475

(4.7%), and Science of the Total Environment (3.14%). The productivity of Water Science and Technology suggests that studies on the application of deep sludge dewatering technology are more prevalent than those on other sludge dewatering techniques. Moreover, the high productivity and IF of Water Research suggest that studies on the mechanisms of deep sludge dewatering constitute a research hotspot.

3.4. Statistical analysis of countries and authors

The statistical analysis revealed that 102 countries/regions contributed to sludge dewatering research between 1993 and 2022. Table 3 enumerates the top 20 most prolific countries/regions in sludge dewatering research. Among these, 9 are in Europe, 7 are in Asia, 3 are in the Americas, and 1 is in Oceania. The two leading contributors are China, producing 2,232 articles (37.21%), and the USA, contributing 633 articles (10.55%). They are followed by Canada (302 articles, 5.04%), Australia (294 articles, 4.9%), Japan (285 articles, 4.75%), and Poland (280 articles, 4.67%). The notable surge in sludge dewatering research in China can be attributed to the country's rapid urbanization and associated increase in municipal wastewater treatment, leading to a considerable generation of sludge. The widespread implementation of deep sludge dewatering processes, aimed at reducing the water content of sludge to 60% or less, further propels research activities in China [2].

Table 3
Top 20 most productive countries/regions from 1993 to 2022

Country/Region	Publications	Percentage (%)
Peoples R China	2,232	37.21
USA	633	10.55
Canada	302	5.04
Australia	294	4.9
Japan	285	4.75
Poland	280	4.67
Germany	193	3.22
England	177	2.95
Spain	176	2.93
France	159	2.65
Taiwan	155	2.58
Turkey	151	2.52
Italy	143	2.38
South Korea	130	2.17
Denmark	117	1.95
India	100	1.67
Singapore	90	1.5
Sweden	89	1.48
Ireland	81	1.35
Brazil	78	1.3

Fig. 4 showcases a network diagram, created using VOSviewer software, which illustrates the cooperation between countries and regions in sludge dewatering research. The diagram indicates that China and the USA are the most active in international collaboration on sludge dewatering research. After 2014, China emerged as the country with the highest degree of cooperation with other nations in this field, a distinction previously held by the USA.

A total of 13,078 authors contributed to sludge dewatering research between 1993 and 2022. Table 4 lists the top 10 most published authors. Lee DJ was the most prolific, having published about 75 papers on sludge dewatering, and also boasts the highest h-index. Following Lee DJ was Zhao YQ, who published 65 papers and holds an h-index of 43. Subsequently, we have Dai XH (63 papers, h-index 47) and Zheng HL (54 papers, h-index 46). These rankings highlight these authors' substantial contributions and significant impact on sludge dewatering research.

Fig. 5 presents the co-authorship network diagram of authors, where the minimum number of documents per author was set at 10. This criterion was met by 171 notable authors. Authors within the same color-coded clusters suggest a higher degree of collaboration among them. Larger nodes represent highly productive authors such as Wang DB, Yang JK, Dai XH, Wang DS, and Zheng HL, who have made substantial contributions to the field. There are also key collaborations evident among certain researchers. For instance, Dai XH collaborates closely with researchers including Yang JK, Wang DB, Zhou Z, Li Z, and others. Similarly, Yang JK has collaborations with authors such as Yao H, Yuan ZG,

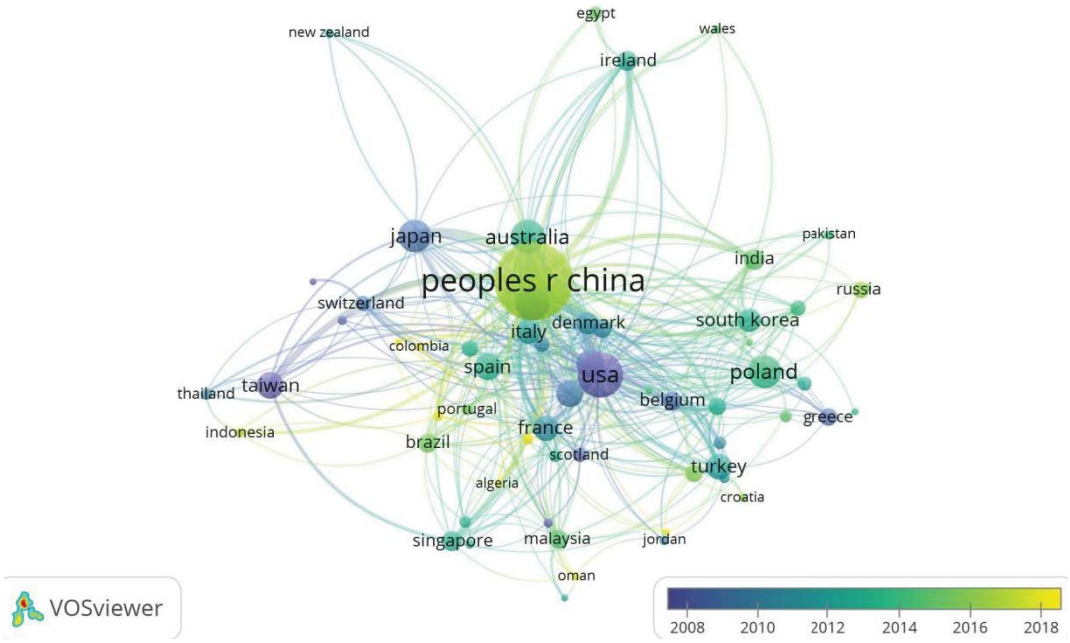


Fig. 4. Countries or regions of co-authorship in sludge dewatering studies in 1993–2022.

Table 4
Top 10 most productive authors from 1993 to 2022

Authors	Publications	h-index	Citations
Lee DJ	75	49	9,258
Zhao YQ	65	43	6,556
Dai XH	63	47	9,929
Zheng HL	54	46	6,578
Zhang WJ	53	41	4,076
Wang DB	52	26	2,130
Wang DS	52	148	140,793
Novak JT	50	45	6,849
Yang JK	45	51	8,358

Zhou Y, and others. Nghiem JD collaborates with Liu H, Novak JT, Wang QL, Higgins MJ, among others, indicating active research collaboration within the network.

3.5. Statistical analysis of highly cited papers

Papers that are frequently cited often hold considerable academic value and professional impact. Table 5 lists the top 10 highly cited papers in the field of sludge dewatering from 1993 to 2022. Among the analyzed papers, the most cited paper received 2103 citations, with the remaining papers being cited more than 500 times. The distribution of highly cited papers by country is as follows: China, Belgium, the USA, and Canada each contributed two papers, while Greece and Singapore contributed one paper each. Three papers were published in Water Research and two in Journal of Hazardous Materials. Within the top 10 most cited papers, three focused on EPS, and two were reviews specifically discussing sludge dewatering pretreatment methods.

The most cited paper was "A review of classic Fenton's peroxidation as an advanced oxidation technique", discussing the use of Fenton's reagent to improve sludge dewaterability [14]. The activation of H_2O_2 by Fe^{2+} to produce a hydroxyl radical known for its potent oxidative property plays a significant role in degrading EPS. This process leads to the breakdown of EPS molecules, facilitating the release of bound water, and enhancing the dewaterability of sludge. The second most cited paper by [15] examined the impact of EPS on biomass flocculation, sludge settling, and dewaterability, finding that loosely bound EPS (LB-EPS) negatively affects both cell attachment and the structural integrity of sludge flocs, thereby inhibiting the separation of sludge and water during the dewatering process.

The third most cited paper was a study on sewage sludge treatment and final disposal methods in European countries [16]. This paper highlighted that the predominant mechanical sludge dewatering methods used in most European sewage treatment plants include centrifuges, belt filter presses, and filter presses. Yang et al. discussed various aspects of sludge production, management, treatment, and disposal in China [17]. The authors pointed out the incomplete nature of laws and regulations related to sludge management in China. The suggested technical route for sludge treatment and disposal in China, "thickening-anaerobic digestion-dewatering-land application", is deemed feasible, albeit with challenges to be addressed.

He et al. conducted research on the hydrothermal carbonization process, which involves converting sludge into hydrochars at 200°C for different carbonization times [12]. Their findings suggest a reduction in oxygen/carbon and hydrogen/carbon atomic ratios, indicating that dehydration and decarboxylation reactions are important pathways during the process. Pilli et al. [18] summarized the advantages of ultrasonication as a pretreatment method for sludge. The application of ultrasonic pretreatment

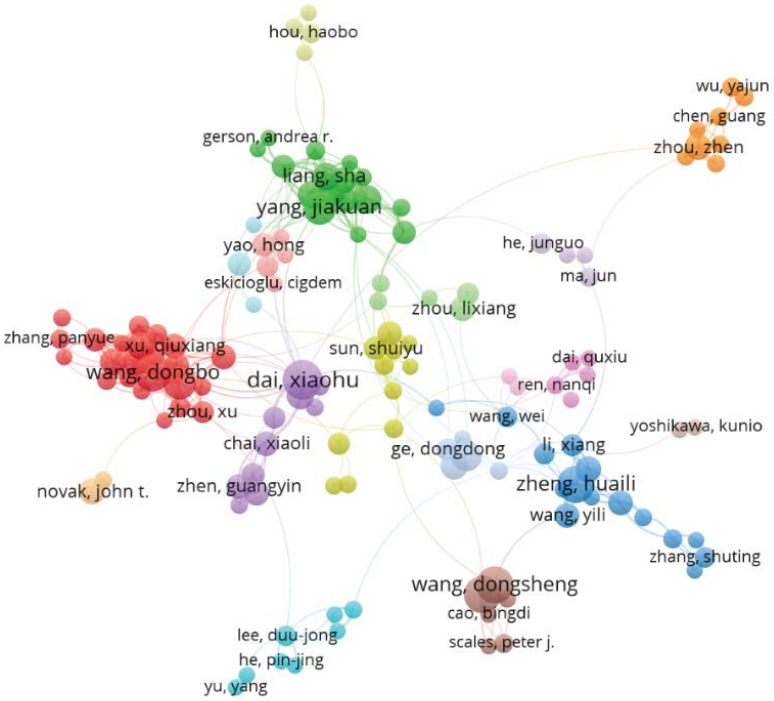


Fig. 5. Maps of author collaborative networks.

Table 5
Top 10 highly cited papers in sludge dewatering

Rank	Authors	Title	Journal	TC	PY	Country
1	Neyens and Baeyens	A review of classic Fenton's peroxidation as an advanced oxidation technique	Journal of Hazardous Materials	2103	2003	Belgium
2	Li and Yang	Influence of loosely bound extracellular polymeric substances (EPS) on the flocculation, sedimentation, and dewaterability of activated sludge	Water Research	1248	2007	China
3	Kelessidis and Stasinakis	Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries	Waste Management	699	2012	Greece
4	Yang et al.	Current state of sludge production, management, treatment and disposal in China	Water Research	692	2015	China
5	Bozell et al.	Production of levulinic acid and use as a platform chemical for derived products	Resources Conservation and Recycling	636	2000	USA
6	He et al.	Conversion of sewage sludge to clean solid fuel using hydrothermal carbonization: Hydrochar fuel characteristics and combustion behavior	Applied Energy	588	2013	Singapore
7	Munir et al.	Release of antibiotic resistant bacteria and genes in the effluent and biosolids of five wastewater utilities in Michigan	Water Research	561	2011	USA
8	Neyens et al.	Advanced sludge treatment affects extracellular polymeric substances to improve activated sludge dewatering	Journal of Hazardous Materials	557	2004	Belgium
9	More et al.	Extracellular polymeric substances of bacteria and their potential environmental applications	Journal of Environmental Management	525	2014	Canada
10	Pilli et al.	Ultrasonic pretreatment of sludge: A review	Ultrasonics Sonochemistry	521	2011	Canada

TC: Total citations; PY: Publication year.

enhances the dewaterability of sludge, potentially reducing the sludge cake volume by up to 31%.

3.6. Statistical analysis of keywords

The analysis of keyword co-occurrence can offer deep insights into research hotspots and trends within the field of sludge dewatering. In total, 14,214 author keywords were extracted from keyword statistics for the period 1993–2022, with 438 of these keywords appearing more than 20 times. For more precise visualization, repetitive or irrelevant keywords like sludge dewatering, sludge, dewatering and dewaterability were excluded. After the screening process, a pool of 229 keywords that are relevant to sludge dewatering was identified.

Anaerobic digestion was the most frequent keyword, appearing 327 times. This was followed by extracellular polymeric substances (163 times), conditioning (133 times), and heavy metals (119 times). In the keyword network view depicted in Fig. 6, the size of the nodes represents the frequency of the keyword's occurrence, with larger nodes indicating higher frequency. In the visualization, the color assigned to each node signifies its level of relevance to sludge dewatering. Nodes of the same color indicate strong relevance, suggesting they are closely related within the context of sludge dewatering. Conversely, nodes of different colors suggest weaker relevance, indicating less connection between them in relation to the topic. The thickness of the lines between nodes represents the intensity of keyword co-occurrence [11].

The red cluster primarily consists of terms related to anaerobic digestion. Key terms within this cluster include "anaerobic digestion", "extracellular polymeric substance", "biogas production", "thermal hydrolysis", and "co-digestion". Anaerobic digestion is widely utilized in sludge treatment for biogas recovery, sludge reduction, and stabilization. It is therefore not surprising that more than half of European sewage plants employ the anaerobic digestion process. Recently, the Chinese government has also been promoting the use of anaerobic digestion for sludge treatment, making the dehydration of anaerobically digested sludge a focal point of research [10].

Extracellular polymeric substances (EPS) are highly hydrophilic and significantly influence sludge dewaterability [19]. EPS generally has a three-layer structure, consisting of an outer layer of dissolved EPS (S-EPS), a middle layer of loosely bound EPS (LB-EPS), and an inner layer of tightly bound EPS (TB-EPS). EPS composition includes proteins, polysaccharides, humic substances, and nucleic acids. Consequently, conditioning technologies that target the structure of EPS layers and sludge composition are being explored to facilitate cell cracking, degrade EPS components, and regulate the sludge structure, ultimately improving sludge dewatering [10].

The anaerobic digestion process leads to the breakdown of EPS and its release into liquids. However, this results in degraded sludge filterability due to the formation of fine particles and the release of biopolymers [2]. Therefore, various pretreatment methods for anaerobically digested sludge have been explored, including skeleton building, thermal hydrolysis, ozonation, chemical oxidation, and electrolysis [20,21].

The clusters colored green and light blue primarily contain terms focused on sludge conditioning, sludge characterization, and dewatering equipment technology. The green cluster showcases keywords such as "conditioning", "flocculation", "rheology", "filtration", and "coagulation". A fewer number of keywords are found in the light blue cluster, which include "kinetics", "electro-dewatering", "energy consumption", and "moisture content".

Improvements in sludge dewaterability can be achieved through proper conditioning. Indicators commonly used

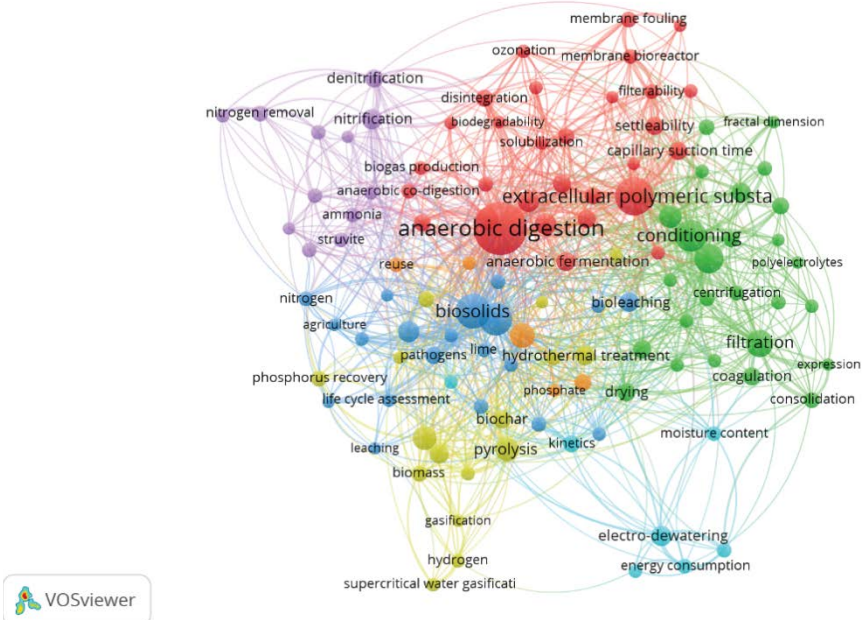


Fig. 6. Co-occurrence of author keyword network for sludge dewatering research.

to assess conditioning effectiveness include capillary suction time (CST) and specific filtration resistance (SRF), with others being the water content of the dewatered sludge, sludge particle size, zeta potential, fractal dimension, and rheological properties of the sludge [22]. Increased dewaterability is closely tied to reductions in CST, SRF, viscosity, and compressibility. It also correlates with an increase in floc size, the release of bound water, and a near-neutral zeta potential [23–25].

Chemical conditioners are frequently added prior to mechanical dewatering to enhance sludge dewatering properties. Extensive research has been conducted on the factors affecting sludge dewatering and on the development of high-efficiency conditioning technologies [4]. Organic flocculants such as polyelectrolytes have been used to lower the specific resistance of sludge [26]. However, the challenge remains to increase filter cake solids solely with polyelectrolyte addition, even with high polymer doses. The incorporation of physical conditioners, or skeleton builders, provides the sludge with a rigid incompressible structure, thereby lowering the water content of the sludge cake [27]. Physical techniques such as electrolysis, microwaving, and ultrasonication have been employed to release water from EPS and to augment sludge dewaterability. Nonetheless, when dealing with large quantities of sludge, these physical methods can be costly, warranting further exploration [28].

The dark blue cluster predominantly includes terms associated with the composting and land use of sludge. "Biosolids", "heavy metals", "composting", and "phosphorus" are among the keywords presented in the dark blue cluster. In regions where topsoil organic matter is lacking, using dewatered and composted biosolids as soil amendments initially appears to be a viable solution that allows for the recycling of organic matter and nutrients such as nitrogen, phosphorus, and potassium [29]. However, the addition of iron salts, aluminum salts, and other metal salts as flocculants for sludge dewatering increases the conductivity of the dewatered sludge cake. If lime is added during sludge dewatering, it will raise the pH of the sludge, potentially affecting its land use. Furthermore, biosolids may contain undesirable substances such as heavy metals, necessitating risk assessments prior to land application [30,31].

The yellow cluster mainly consists of terms associated with the reuse and disposal of dewatered sludge. The keywords found in the yellow cluster include "hydrothermal carbonization", "pyrolysis", "gasification", and "biochar". Advantages of hydrothermal carbonization of sludge encompass climate change mitigation and environmentally safe sludge disposal. The product of hydrothermal carbonization, sludge-based biochar, can be employed as an adsorbent for water and wastewater treatment [32]. Yuan and Dai [33] demonstrated that PFC-pretreated sludge, post-pyrolysis, was suitable for the Fenton reaction. Yu et al. [34] attempted to produce sludge biochar using $Fe_2(SO_4)_3$ to minimize biocrude production from sludge pyrolysis. Mainardis et al. [35] utilized four different pretreatment technologies combined with biochar addition to increase biogas production from sludge, also conducting a life cycle assessment.

The purple cluster is primarily populated by terms related to sludge treatment wetlands or drying reed beds. Keywords highlighted in the purple cluster encompass "struvite", "phosphorus removal", "nitrogen removal", "nitrification", "denitrification", and "constructed wetlands". For over three decades, sludge treatment wetlands have been utilized for sludge dewatering, with major benefits being low energy consumption, decreased maintenance costs, and environmental sustainability [36]. Dewatering processes in sludge treatment wetlands under different operational parameters (such as influent sludge, plant species, organic loading rate) and climatic conditions have been investigated [37].

Fig. 7 represents the network and temporal evolution of keyword co-occurrence. The timeline is suggested by the color of the nodes, indicating three temporal phases. The initial phase, likely before 2008, primarily concentrates on polymer conditioning for centrifuge dewatering and sludge incineration. The second phase, presumably between 2009 and 2013, mainly focuses on the effect of anaerobic digestion on sludge dewaterability, sludge flocculation, drying, and the presence of heavy metals in dewatered sludge for land use. The third phase, from 2014 to 2022, is primarily concerned with the influences of EPS on sludge dewaterability, dewatering of anaerobically digested sludge via thermal hydrolysis pretreatment, and pyrolysis carbonization for sludge treatment.

The use of citation bursts in keywords is a method that helps identify rapidly proliferating keywords within a specific period. This approach contributes to understanding evolving trends and research hotspots [38]. A keyword co-occurrence network was constructed to analyze sludge dewatering research from 1993 to 2022, with the 20 most significant citation bursts presented in Fig. 8.

In the early stages, the keyword "floc structure" (1997–2005) demonstrated a burst strength of 9.61, reflecting a sustained period of elevated interest. Generally, sludge floc structure is divided into five layers: supernatant, slime, LB-EPS, TB-EPS, and pellet. The distribution of PN and PS within these layers significantly affects sludge dewaterability [39].

The keywords "filtration" (2004–2011), "flocs" (2007–2015), "aerobic digestion" (2008–2011), and "bioflocculation" (2010–2014) experienced burst strengths of 16.69, 18.11, 8.53, and 10.29, respectively. Chemical flocculants improve sludge filterability by decreasing the specific resistance to filtration (SRF), while physical conditioners, as skeleton builders, aid filtration and reduce the moisture content of the sludge cake. Biopolymers in the sludge, released into the liquid phase under aerobic and anaerobic digestion conditions (with a greater release under anaerobic conditions), increase the specific resistance of the sludge and the required flocculant dosage. Numerous bioflocculation studies have employed EPS to improve sludge settling and dewatering. Subramanian et al. discovered that introducing extracted slime EPS from individual strains notably improved sludge dewaterability [40].

Recently, keywords such as "free nitrous acid" (2018–2020), "hydrothermal carbonization" (2019–2022), "iron" (2020–2022), "peroxymonosulphate" (2020–2022), "resource recovery" (2020–2022), and "enhanced dewaterability" (2020–2022) have attracted significant interest. Studies on free nitrous acid, iron, peroxymonosulphate, and other advanced oxidation pretreatment methods to

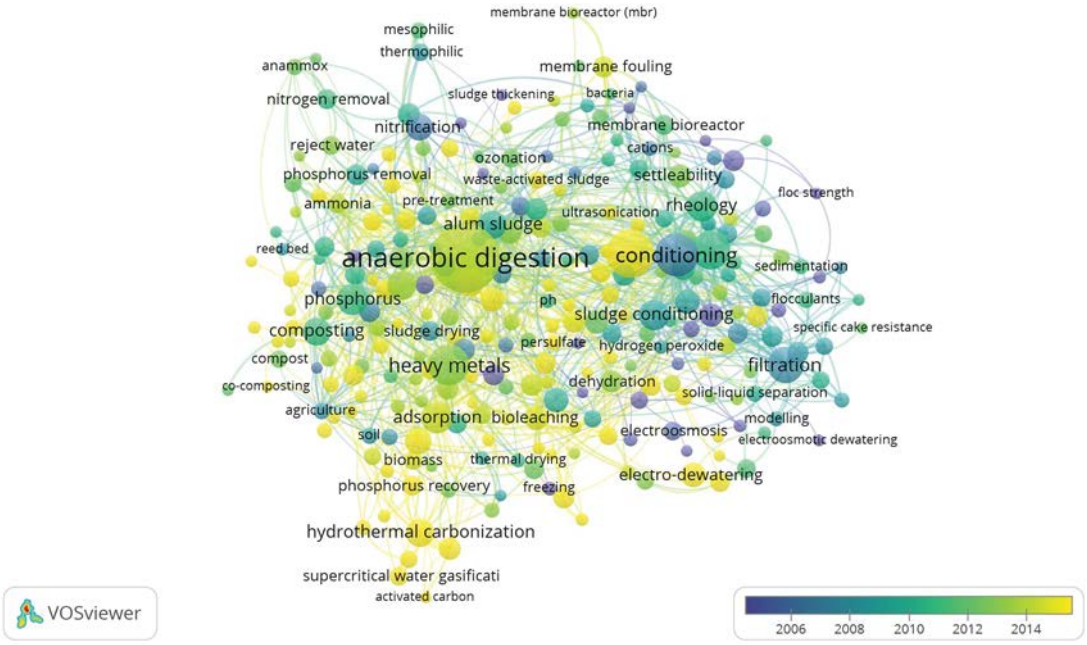
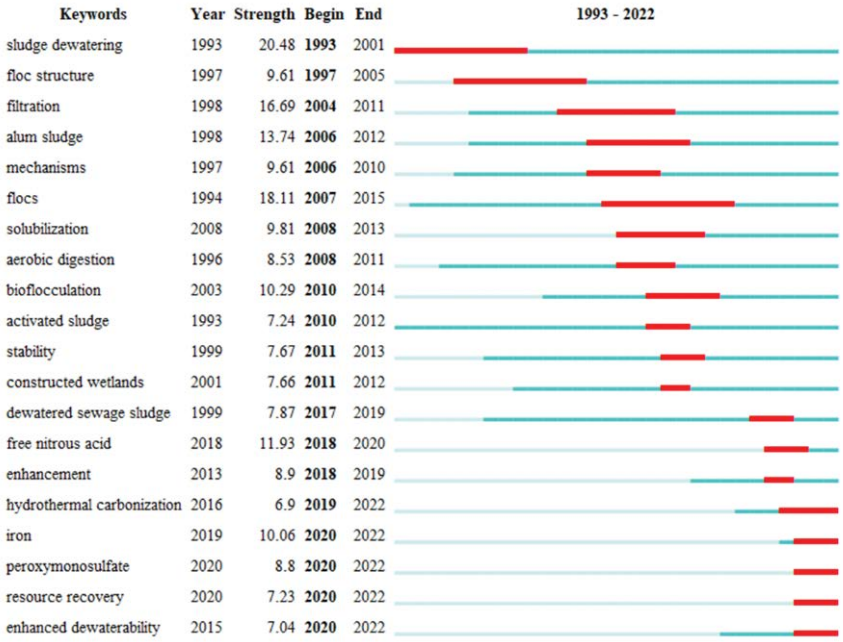


Fig. 7. Temporal development of the network in terms of keyword co-occurrence.



Keywords	Year	Strength	Begin	End
sludge dewatering	1993	20.48	1993	2001
floc structure	1997	9.61	1997	2005
filtration	1998	16.69	2004	2011
alum sludge	1998	13.74	2006	2012
mechanisms	1997	9.61	2006	2010
flocs	1994	18.11	2007	2015
solubilization	2008	9.81	2008	2013
aerobic digestion	1996	8.53	2008	2011
bioflocculation	2003	10.29	2010	2014
activated sludge	1993	7.24	2010	2012
stability	1999	7.67	2011	2013
constructed wetlands	2001	7.66	2011	2012
dewatered sewage sludge	1999	7.87	2017	2019
free nitrous acid	2018	11.93	2018	2020
enhancement	2013	8.9	2018	2019
hydrothermal carbonization	2016	6.9	2019	2022
iron	2019	10.06	2020	2022
peroxymonosulfate	2020	8.8	2020	2022
resource recovery	2020	7.23	2020	2022
enhanced dewaterability	2015	7.04	2020	2022

Fig. 8. Top 20 keywords with the most significant citation bursts.

enhance sludge dewatering performance have emerged as trending topics [5,41,42]. The hydrothermal carbonization process can notably enhance sludge dewatering and convert sludge into high-value products, thereby facilitating resource recovery. Recent advancements suggest that the primary mechanisms of hydrochar formation include the solid–solid conversion of insoluble sludge components and the polymerizations of highly reactive intermediates from biopolymer degradation [43].

3.7. Analysis of research hotspots in China, the USA, and the EU

The focus areas of sludge dewatering research in China, the USA, and the EU were identified using data derived from academic papers published over the past 5 y. Between January 1, 2018, and December 31, 2022, Chinese researchers published 1,283 articles on sludge dewatering, while the USA and the EU published 130 and 536 papers, respectively. Fig. 9 displays the density visualization maps

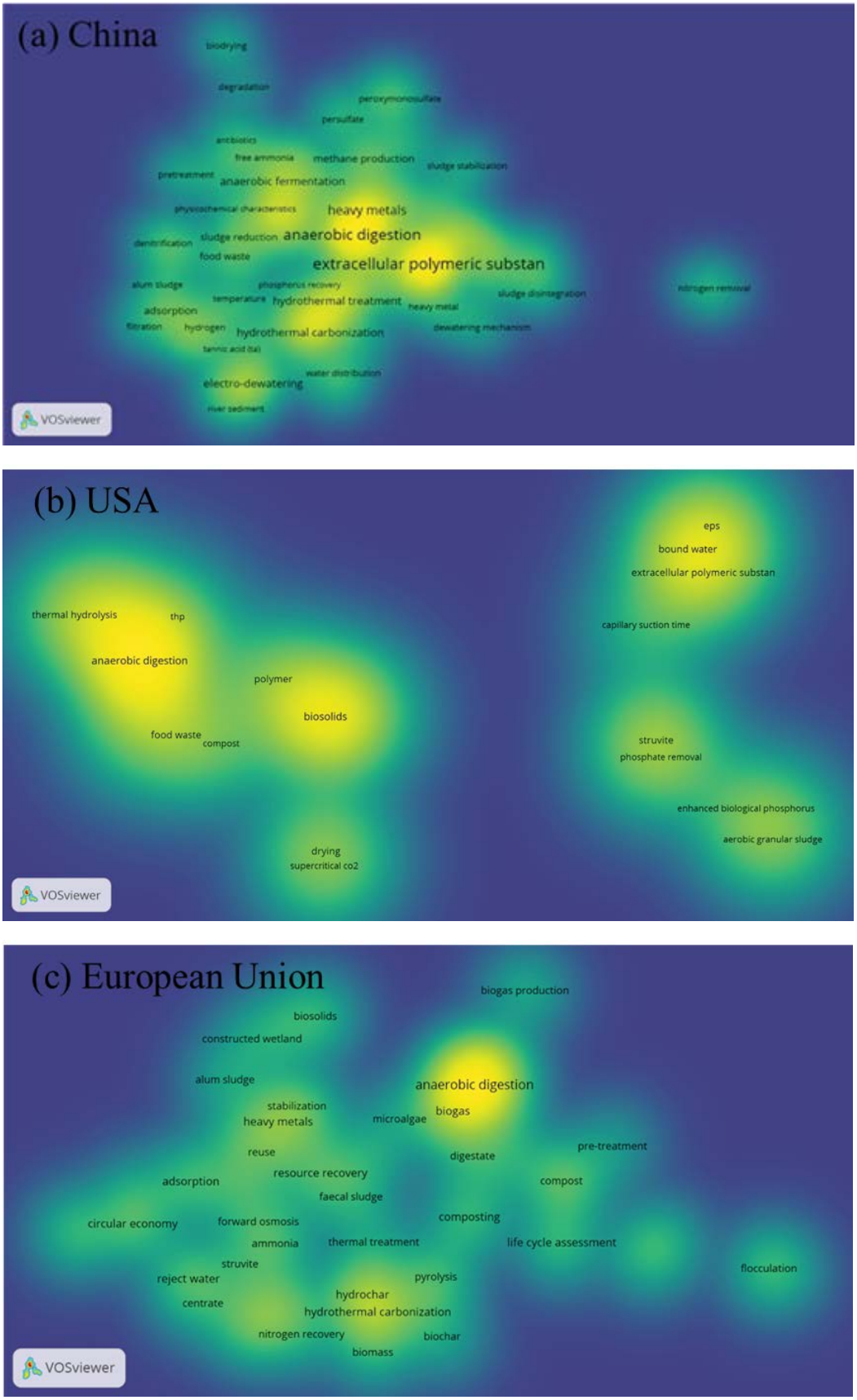


Fig. 9. Density visualization related to sludge dewatering research hotspots from 2018 to 2022: (a) China, (b) the USA, and (c) the EU.

concerning research hotspots in sludge dewatering from 2018 to 2022; the research hotspots are represented by yellow areas. Over this 5-y period, the number of papers on sludge dewatering published by the USA researchers was relatively lower, leading to a more concentrated set of keywords. With more papers published, the keyword density maps for China and the EU display more yellow areas.

A comparative study of the research hotspot density maps from these three regions reveals that anaerobic digestion was a focal point in each area. Several studies in China and the USA delved into thermal hydrolysis and EPS. China and the EU also placed significant emphasis on hydrothermal carbonization and heavy metals as part of their resource recovery research from dewatered sludge. In the USA, researchers explored the drying effect of supercritical CO_2 extraction on municipal sewage sludge, finding that under certain conditions, supercritical CO_2 extraction could reduce the water content of municipal sludge from 89% to 53% within 15 min [44]. The impact of continuous flow aerobic granulation on downstream sludge dewatering was another subject of research in the USA. While thickened aerobic granular sludge was effective in dewatering, it was observed that such sludge rapidly lost its dewatering advantage once it disintegrated under shear forces comparable to those of industrial dewatering centrifuges [9].

In recent years, European research has placed increasing emphasis on life cycle assessment and circular economy. For instance, Zhang et al. [45] carried out a study using life cycle assessment methodology to evaluate the feasibility of incorporating an electro-dewatering upgrade into an Italian wastewater treatment plant. Their findings suggest that the addition of this unit to existing conventional dewatering units is both economically and environmentally feasible, especially when the sludge disposal method involves incineration. Gievers et al. [46] utilized a life cycle evaluation to estimate the environmental impact of sewage sludge pyrolysis. They discovered that the combined use of biochar in horticulture and pyrolysis could result in an approximate 78% reduction in CO_2-equivalent emissions compared to standalone incineration. This strategy of pyrolyzing digested sewage sludge, combined with the appropriate use of biochar, not only aids nutrient cycling but also promotes carbon sequestration.

4. Conclusions

This bibliometric study, using the WoS Core Collection database, analyzed sludge dewatering research from 1993 to 2022. The results demonstrated a consistent increase in the total number of papers on sludge dewatering in recent years. China and the USA, being the most prolific publishers, also collaborated most in this field. With 2,232 papers, accounting for 37.2% of the total publications, China emerged as the leading country. Furthermore, three out of the top 10 most cited papers were from China, highlighting China's significant role in sludge dewatering research.

According to the keyword clustering, anaerobic digestion emerged as the most frequently used keyword. Recent research hotspots included the investigation into the influence of extracellular polymeric substances on sludge dewaterability, the utilization of thermal hydrolysis to improve anaerobic digestion of sludge, and the study of hydrothermal carbonization and heavy metals extraction for sludge reuse and disposal.

Over the past 5 y, research on sludge dewatering in China, the USA, and the EU displayed varying focus areas. Several studies in China and the USA explored thermal hydrolysis and EPS. Meanwhile, hydrothermal carbonization and heavy metals were prominent subjects of investigation in both China and the EU. Additionally, there has been a growing interest in life cycle assessment and circular economy within European studies.

Statements and declarations

Author contributions

Feng Hou - Methodology.
Jinghui Zhang - Investigation, Methodology, Writing.
Lili Gan - Resources, Writing - Review & Editing.
Hongtao Pang - Resources.
Guoguang Zhai - Formal analysis.
Weiping Qiao - Supervision.

Data availability

Datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interest

The authors declare no conflict of interest.

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