Bibliometric analysis of research trends in biogranulation technology for wastewater treatment

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ABSTRACT

Inadequate wastewater management and treatment can lead to environmental pollution, deterioration of water quality, depletion of water resources, and adverse effects on human well-being. The utilization of biogranulation technology for treating domestic and industrial wastewater has witnessed increasing adoption among both academics and industrial players. However, there is a lack of comprehensive bibliometric analysis examining the current and emerging research trends. To bridge this gap, the present study utilized data from the Scopus database between 1992 and 2022 for bibliometric analysis, while leveraging the VOSviewer program and the R-studio package for data mapping. The search conducted on the scientific database yielded a substantial collection of 1703 research articles. Notably, China emerged as the foremost country in terms of publication output, with Jin Rencun recognized as the most prolific author. The journal with the highest publication count was identified as Bioresource Technology, while the dominant subject area proved to be Environmental Science. Among the institutions, Harbin Institute of Technology stood out as the leading contributor in this field of study. Visualization mapping of the data demonstrated that "aerobic granular sludge" was the most prominent author keyword in the field, while "sequencing batch reactor" emerged as the most significant research term. This bibliometric analysis extensively explored various research areas within the domain of biogranulation technology for wastewater treatment, encompassing reactor types, wastewater classifications, sludge-related terminology, chemical characterization, granulation aspects, microbial studies, physical properties, and processes/mechanisms. The findings of this study offer valuable insights to researchers, practitioners, and stakeholders, facilitating the advancement of biogranulation technology for wastewater treatment and aiding in informed decision-making.

Keywords: Bibliometric mapping; Environmental remediation; Granular development; Wastewater treatment

1. Introduction

Wastewater released from treatment facilities has been widely recognized as one of the most substantial contributors to water and environmental pollution on a global scale (Syahirah et al. 2023). The global industrial demand for water is projected to increase significantly due to factors such as population growth and economic development. The significance of wastewater treatment lies in its ability to safeguard public health and the environment by removing hazardous pathogens and pollutants that are typically present in wastewater before it is released into the environment (Nuid et al. 2023). If wastewater is left untreated or not treated properly, it may contain various contaminants, (i.e., pathogenic microorganisms, chemicals, and other pollutants) that can result in severe health issues such as respiratory, gastrointestinal, and skin infections (Pishgar et al. 2020). More so, wastewater contain toxic heavy metals, phenolic organic compounds, other persistent organic pollutants which require efficient removals/treatment.

Untreated wastewater may also contain nutrients that can lead to harmful algal blooms and ecological imbalances in water bodies (Wang et al. 2022; Omoregie et al. 2023). Hence, wastewater treatment ensures the removal of these contaminants, promoting public health and the environment, while preventing disease transmission and protecting water resources for the future. Unfortunately, wastewater treatment presently encounters several challenges arising from increasing human population growth, limited land space, and inadequate funding for infrastructure upgrades (de Medeiros et al. 2022). To overcome these challenges, sustainable, compact, and cost-effective wastewater treatment methods are needed. These methods should efficiently remove pollutants while minimizing energy and chemical consumption and generating by-products that can be reused or safely disposed of.

Biological treatment methods, such as anaerobic digestion, membrane bioreactors, and biogranulation technology, have been developed and implemented worldwide (Xu et al. 2021; Yaqoob et al. 2022; Kazimierowicz et al. 2023). These methods are preferred over chemical treatments due to their sustainability, cost-effectiveness, simplicity, and environmental friendliness (Basri et al. 2023). Many wastewater treatment methods have been created over time, but each one has its specific limitations which include low efficiency, the inability to handle diverse types of wastewater, generating high amounts of secondary waste, and being costly (Syahirah et al. 2023). However, biogranulation has steadily emerged as a promising approach to treat wastewater. Biogranulation technology is an effective method for treating wastewater that relies on biogranules, which are microbial aggregates that form through a self-immobilization process. These aggregates consist of a diverse community of microorganisms that work together to degrade organic and nutrient compounds in wastewater (Meng et al. 2020). The process of biogranulation involves the gradual formation of small microbial aggregates that grow in size and complexity over time as microorganisms colonize their surfaces (Ali et al. 2021). The biogranules possess specific physical characteristics, including a compact structure and regular shape, that allow for excellent settling ability and facilitate the efficient separation of sludge from treated effluent (We et al. 2021). Biogranules also exhibit high biomass, enabling them to rapidly remove pollutants from wastewater (Wang et al. 2022). They have a high surface area and porosity, which enhances their resilience to toxic substances (Gomez-Gallegos et al. 2021). Moreover, biogranulation technology is cost-effective and sustainable as the biogranules can be easily harvested and reused with low-energy inputs. Biogranulation technology is highly tolerant of high organic loads and can simultaneously remove organic substances and nutrients, making it an important tool in sustainable wastewater treatment (Ali et al. 2021; Nuid et al. 2023).

Over the years, biogranulation technology has been increasingly recognized as a promising substitute for traditional approaches in wastewater treatment worldwide. Previously, studies on biogranulation technology primarily focused on the mechanisms of granule formation, the physical properties of granules, and the performance of granular systems in treating wastewater (Liu et al. 2004; Ni et al. 2015). However, the development of advanced microscopy and imaging techniques in recent years has enabled a better understanding of the microbiology and biochemical mechanisms involved with biogranulation (Liu et al. 2013; Tao et al. 2017; Nancharaiah and Kiran Kumar Reddy 2018). Currently, biogranulation technology is considered an emerging and promising wastewater treatment approach. Biogranulation provides versatility in developing biogranules by employing both aerobic and anaerobic processes. In aerobic biogranulation, the system is supplied with oxygen to support the growth of aerobic microorganisms that form the biogranules (Czarnota and Masłoń 2019; Nuid et al. 2023). This method proves effective in eliminating organic pollutants and nutrients from wastewater. Conversely, anaerobic biogranulation creates an oxygen-deprived environment where anaerobic microorganisms thrive and create biogranules (An et al. 2021). This approach is particularly well-suited for treating high-strength industrial wastewater, as anaerobic microorganisms efficiently convert complex organic compounds into biogas and stable by-products (Wang et al. 2022; Omar et al. 2023). The adaptable nature of biogranulation to accommodate aerobic and anaerobic conditions makes it an adaptable and promising solution for wastewater treatment. Therefore, this biological technology is a suitable and effective approach to efficiently tackle a wide range of pollutants and adapt to the varying characteristics of wastewater.

Biogranulation technology has the potential to contribute significantly to multiple United Nations Sustainable Development Goals (SDG), including clean water and sanitation (SDG 6), responsible consumption and production (SDG 12), and affordable and clean energy (SDG 7). As research on biogranulation technology in wastewater treatment continues to expand, it is crucial to organize, summarize, and quantify the latest advancements. Bibliometric analysis, a widely used approach, enables the evaluation of global research activities by analyzing published articles in scientific databases such as Scopus, Web of Science, and Dimensions (Usman and Ho 2021; Islam et al. 2022; Omoregie et al. 2022). This method proves valuable in quantitatively assessing trends and patterns in scientific literature, as well as evaluating research trends and development status (Purba et al. 2022). Consequently, the bibliometric analysis serves as a useful tool for assessing the current state of research in the field, identifying potential areas of collaboration among researchers and institutions, and gaining insights into the progress made in biogranulation technology.

Several bibliometric analyses have been conducted, each focusing on specific aspects of bio-granulation technology. In **Table 1**, these analyses are summarized, highlighting the main research themes and underscoring the uniqueness of the current article. Each of these studies has contributed valuable insights to wastewater treatment research, identifying trends, gaps, and potential future directions within their respective fields. However, the limitations of previous papers were evident. Some studies solely concentrated on granular sludge or the microalgae aspect of the field, resulting in an incomplete analysis of the broader biogranulation domain. Additionally, others employed limited keywords to retrieve relevant articles related to biogranulation technology, as depicted in **Table 1**. To address these gaps and offer a comprehensive overview of biogranulation technology for wastewater treatment between 1992 and 2022 from Scopus database, the present study aims to map research trends and patterns. This includes examining publication and citation H-index outputs, identifying productive countries, influential journals, prolific authors, and significant institutions in the field. Furthermore, the study investigates publication and citation trends over the given period, shedding light on the growth or decline of contributing factors. Through the use of VOSviewer program and R-studio package, the research also pinpoints emerging areas of interest and highlights author keywords hotspot. This approach ensures a thorough and holistic analysis of biogranulation technology, contributing significantly to the existing body of knowledge in the field of wastewater treatment research.

2. Methodology

2.1. Data source and search strategy

Bibliometric analysis offers valuable insights into the patterns, trends, and impact of scientific publications, aiding in the identification of research gaps and facilitating further investigation in specific areas. Given the specific research question, it is more suitable to employ quantitative analysis using pre-existing data from scientific databases (Hasan et al. 2023). The methodology chosen does not lend itself well to conducting meta-analyses, as meta-analyses rely on existing empirical results to summarize new findings in the scientific literature (Linnenluecke et al. 2020). Hence, this study adopts a straightforward bibliometric approach by sourcing datasets from the Scopus database due to its reputable standing as one of the most well-known and reliable sources for bibliometric studies. Scopus is easily accessible through the online library systems of most universities, ensuring the convenient availability of data for researchers (Hasan et al. 2023). More so, the scientific database offers a wide range of scholarly literature, including abstracts and citations, making it a comprehensive and valuable resource (Omoregie et al. 2022). Bibliometric data were retrieved from the online database Scopus on 23 April 2023, covering for documents on biogranulation treatment of wastewater from 1992 to 2022. The query string used for the search was: TITLE-ABS-KEY ((biogranulation) OR (granular AND sludge AND process) OR (microbial AND granulation) OR (biogranules) OR (granulation AND technology) AND (wastewater AND treatment)). These keywords are related to various aspects of the biogranulation technological process in wastewater treatment, encompassing these terms represent the key components and methods involved in biogranulation, a process used for efficient and effective treatment of wastewater.

2.2. Data extraction and analysis

The study retrieved a total of 2,608 documents from the Scopus database, with 422 classified as open access. Among the open access publications, 135 were in the gold category, 70 were Hybrid Gold, 73 were Bronze, and 270 were classified as Green. The documents covered a diverse range of types, with articles being the most prevalent (2,146), representing approximately 82.19% of the retrieved documents. Conference papers (225) and reviews (172) were also prominent. The database primarily consisted of journal articles (2,350), followed by conference proceedings (135), book series (78), books (31), and trade journals (11). The majority of the documents were in English (2,416), with smaller numbers in Chinese (164), German (4), Japanese (4), Portuguese (3), French (2), Polish (2), Russian (2), Spanish (2), and one each in Czech, Malay, Persian, and Turkish. Additionally, there were eight documents where the language was undefined. The "Undefined" category in language refers to documents where language identification was not possible due to missing or incomplete metadata, technical issues, or other challenges. The query strings were subsequently limited only article publications written in English language and published in journals from 1992 to 2022 (as shown in **Supplementary information, Table S1**). Authors frequently prioritize articles written in English as their preferred document type for bibliometric analysis. The popularity of English-language articles for bibliometric analysis stems from their broad availability, easy accessibility, and the prevailing use of English as the primary language for scholarly communication worldwide (Saravanan et al. 2022). This study centered its analysis on research articles to precisely examine the research present and emerging trends (Purba et al. 2022).

In bibliometric analysis, datasets exported from the Scopus database play a crucial role as they encompass a wide array of information necessary for studying patterns, trends, and impact within scholarly literature. These datasets typically consist of publication titles, author names, affiliations, publication dates, citation counts, H-index values, abstracts, keywords, subject classifications, and other relevant metadata. To facilitate further analysis and visualization in bibliometric studies, the bibliometric datasets are exported from the Scopus database in comma-separated values (CSV) file format. These CSV files contain a diverse range of information, including citation details, bibliographic data, abstracts, keywords, and other related information. The availability of such comprehensive datasets allows researchers to explore and gain insights into various aspects of scholarly publications. By utilizing these datasets, researchers can delve into the analysis of citation patterns, author collaborations, publication trends, and the impact of specific keywords or subject areas. The CSV files serve as valuable resources for conducting in-depth bibliometric analyses and generating visual representations of the findings. The analysis and graphical representation of record details were performed using GraphPad Prism 9.5.1 (GraphPad Software, Inc., located in San Diego, California, USA). This analysis involved examining various aspects such as yearly research publication and citation output, prominent countries, authors, journals, institutions, subject areas, keywords, and research directions. The software facilitated the generation of graphs to visualize and interpret the findings.

2.3. Bibliometric analysis using VOSviewer and R-studio

For this study, VOSviewer program and R-studio software were both used to analyse the CSV text file obtained from Scopus database. VOSviewer software (version 1.6.19, Leiden University, Leiden, Netherlands) is a sophisticated tool is extensively employed for the visualization and analysis of bibliometric networks (Van Eck and Waltman 2010). VOSviewer has been developed using the Java programming language. It facilitates the creation of visual depictions of networks by leveraging bibliographic data, including co-authorship networks and keyword co-occurrence networks (Purba et al. 2022). In VOSviewer, nodes representing entities (such as authors, countries, or keywords) are connected to form clusters based on their similarities or relationships. Each cluster group is visually distinguished by a specific colour, allowing for easy differentiation and identification of distinct clusters within the network visualization (Hasan et al. 2023). Furthermore, within the VOSviewer analysis, each link between nodes is assigned a value known as link strength, which signifies the significance or importance of the relationship. A higher link strength value indicates a stronger association or connection between the two terms being linked (Ilmasari et al. 2022).

Co-authorship analysis involves analyzing the collaborative relationships and patterns between authors or countries by studying their shared authorship or co-affiliation in scholarly publications. To analyze the co-authorship network of authors, a total of 3878 authors were identified by VOSviewer software. The minimum number of published documents by an author was set to 3, and the number of citations by an author was set to 0. This resulted to 759 authors, indicating they met the threshold. However, only 695 authors were found to have connections with each other within the network. On the other hand, to analyze the co-authorship network of countries in the field, a total of 74 countries were identified and met the thresholds (the minimum number of published documents by a country was set to 1, and the number of citations by a country was set to 0). However, only 69 countries were found to have connections with each other within the network. The countries were categorized into separate clusters based on their respective continents. The countries associated in the study were grouped into six distinct categories based on their continents, namely Asia, Europe, America, Africa, and Oceania. In the bibliometric map, countries belonging to the same group were visually represented using the same colour, making it easier to identify groups and patterns based on the continents they belong to (Purba et al. 2022).

Co-occurrence analysis of author keywords is an approach employed to investigate the occurrence and patterns of keywords in academic papers, unveiling their connections and relationships within a specific research field. This method allows researchers to explore the frequency of keywords appearing together, providing insights into the associations and interrelationships among them in the scholarly literature. To analyze the co-occurrence network of keywords in the field, a total of 3533 author keywords were identified. Of these keywords, 571 met the threshold (the minimum number of occurrences of an author keyword was set to 2). However, only 544 author keywords were found to have connections with each other within the network. The analysis of this selected group of author keywords revealed the presence of 84 distinct clusters. Furthermore, the co-occurrence analysis of text data for research terms involves examining the frequency and patterns of how specific terms appear together in the context of scholarly literature. To identify the major research trend, co-occurrence analysis based on text data from titles and abstract fields was used. Binary counting was selected from the VOSviewer program, and of the total of 29209 terms identified, only 444 met the threshold (the minimum number of occurrences of a term was set to 10). However, since VOSviewer only analysis 60% of identified terms (Van Eck and Waltman 2010), a total of 266 research terms were then selected by the software to produce co-occurrence network visualization map of research topics.

R-Studio is a powerful data analysis and programming tool that provides a comprehensive set of tools and features to efficiently analyze and manipulate text files containing publication data. The primary idea behind RStudio is to provide a user-friendly interface and a range of built-in functionalities that streamline the entire data analysis workflow. The significance of RStudio lies in its ability to enhance productivity and reproducibility in publication data analysis plots, and results in a single workspace, that allows researchers to create dynamic and customizable reports, making it easier to share findings and collaborate with peers (Alhassan et al. 2022). In order to conduct data analysis using RStudio, a series of steps are undertaken. Initially, the essential R packages, such as "bibliometrix" are imported to facilitate data handling (Aria and Cuccurullo 2017). Subsequently, the Scopus data is exported in the BibTeX format and retrieved for analysis. The BibTeX file is then loaded into RStudio using the "bib_reader" function from the bibliometrix package. Once imported, the data is subjected to cleaning and preprocessing procedures, involving the elimination of duplicates and irrelevant entries, as well as performing necessary data transformations. Key variables from the dataset, such as publication year, authors, journal, and citation counts, are extracted to uncover patterns and trends. Finally, statistical analyses, including the calculation of citation metrics and conducting co-authorship network analyses, are executed using appropriate R functions and packages. It is imperative to diligently document the steps undertaken, interpret the results, and draw meaningful conclusions based on the findings of the data analysis.

3. Results and Discussion

3.1. The publication and citation trends

The annual distribution of publications on biogranulation technology for wastewater treatment provides insights into the progress, knowledge growth, and advancement of this area. **Fig. 1** displays the fluctuating trends in publication output, citations, and H-index for articles published in this field over time. The initial exploration into this field can be traced back to 1969 when Rizzo and Schade (1969) published the first research article on biogranulation technology. Notably, only one article was published during that particular year, marking the modest beginnings of research in this area. The analysis highlights that the number of publications has consistently increased over time, with a sharp surge since the early 2000s. Notably, the year 2004 stands out as a crucial milestone when the number of publications spiked, with 30 articles published, more than double the number published in the previous year. Despite minor fluctuations as demonstrated in **Fig. 1(a)**, the increase in publications has been steady. For instance, there were slight dips in the number of publications in 1999 and 2011, but these are negligible compared to the overall increase. From 1992 to 2022, the cumulative publication output in the field has experienced a substantial increase, rising from a mere 4 articles to a total of 1703. Additionally, the cumulative percentage of publications reveals that almost 19% of the total publications were published by 2009. By 2022, this figure had reached 100%, indicating that the field of biogranulation technology for wastewater treatment has grown significantly and attracted significant attention from researchers over time.

The field of biogranulation technology for wastewater treatment has continued to experience rapid growth, leading to a notable rise in the overall number of publications. Despite the global COVID-19 pandemic in 2020, the number of scientific publications in this field remained on an upward trajectory. For instance, in 2019, the year saw a total of 156 articles published. Despite the pandemic, the number of publications rose to 171. The number of publications experienced a further surge, reaching 217 articles in 2022. Based on this trend, it is reasonable to anticipate that the number of annual publications will continue to increase in the future, reflecting the ongoing advancements and interest in biogranulation technology for wastewater treatment. **Fig. 1(b)** demonstrates the patterns of citations and the H-index over time in the field of biogranulation technology for wastewater treatment from 1992 to 2022. The H-index, which is a metric that combines the number of publications and the number of citations they receive, indicates a steady increase in the impact and influence of the research in the field, starting from 4 in 1992 to 39 in 2010. However, the H-index declines to 13 in 2022, indicating a decline in the impact of the research in the field. Similarly, the number of citations received by publications in the field of biogranulation technology for wastewater treatment shows an upward trend, starting from 0 citations in 1992 to 10021 citations in 2022. This indicates that the research in the field is gaining more recognition and attention from the scientific community. However, there are fluctuations in the number of citations over time, with a peak in 2019 followed by a decline in 2020 and 2021.

While the research in the field has gained more attention and recognition, the H-index may not always reflect the full impact of the research. For instance, the H-index increases from 4 in 1992 to 39 in 2010, but the number of citations per year increases more rapidly from 0 in 1992 to 1036 in 2010. The reason H-index and citation metrics are not always positively correlated is that the H-index is a measure of both the number of publications and the number of citations that those publications have received (Omoregie et al. 2022). This means that the H-index reflects both the productivity (number of publications) and the impact (number of citations) of a researcher's work. Therefore, while the H-index and the number of citations is related measures of a researcher's impact, they do not always move in lockstep and can provide different perspectives on the researcher's overall influence in their field. The sustained increase in publications and the growing interest from researchers suggest that biogranulation technology is a promising solution for wastewater treatment, with the potential to enhance sustainability and reduce costs (Tan et al. 2021). However, the field of biogranulation technology for wastewater treatment is subject to several factors that impact the fluctuation of publications over time such as the availability of funding for research, the availability of qualified researchers, and technological advancement (Ilmasari et al. 2022). The emergence of new trends and research areas can also impact publication fluctuation. As new research areas emerge, researchers may shift their focus away from biogranulation technology for wastewater treatment, resulting in a decrease in publications (Tan et al. 2021).

3.2. Geographical distribution and top leading countries in the field

Fig. 2 illustrates the research publication trends concerning biogranulation technology for wastewater treatment. The findings indicate that a total of 70 countries worldwide have made contributions to the field between 1992 and 2022. Several countries have emerged as leaders in the field of biogranulation technology for wastewater treatment based on their publication output. China takes the lead with 782 articles and accounts for 33.36% of the total publications in this field. This was distantly followed by the United States with 142 articles, the Netherlands with 131 articles, and Japan with 109 articles. The remaining countries that have also significant contributions in the field include Spain, Taiwan, Italy, Canada, Singapore, and Australia having 85, 65, 63, 58, 57, and 53 articles, respectively. The combined publication outputs of these countries, excluding China, represent 32.55% of the total publications in the field.

Several countries have published relatively few articles on biogranulation technology for wastewater treatment as demonstrated in **Fig. 2**. These countries include Costa Rica, Cuba, Ethiopia, Kenya, Latvia, Lithuania, Macao, Morocco, Nigeria, Oman, and Puerto Rico, with only one article published each. There could be various reasons why these countries have limited publication output on this topic, including a lack of research infrastructure, limited funding, a shortage of expertise in this field, language barriers, or a focus on other research areas (Ilmasari et al. 2022; Purba et al. 2022). One potential factor that may contribute to lower publication outputs in certain countries compared to others is the phenomenon of scholars migrating to other countries and affiliating themselves with universities in those countries. This can pose challenges in accurately attributing contributions to specific countries. To address this issue, it could be beneficial for databases like Scopus and other scientific databases to consider including information about scholars' nationalities, in addition to their affiliations with particular countries. By incorporating this additional data, a more comprehensive understanding of the contributions made by various countries in the field of research can be achieved. An examination of data presented in **Fig. 2** provides insights into the leading countries in research on biogranulation technology for wastewater treatment across different continents. In Asia, China stands out as the clear frontrunner, which is to be expected considering its rapid economic growth and population size (Chen et al. 2015). The United States takes the lead in North America, reflecting its longstanding commitment to research and development in various technological fields, including environmental protection (Omoregie et al. 2022). In Europe, the Netherlands leads the way with 131 articles published, owing to its advanced water management systems and sustainable practices. Australia emerges as the leading country in Oceania, contributing 53 articles, potentially driven by the unique environmental challenges it faces. In South America, Brazil takes the lead with 50 articles published, likely propelled by its expanding population and a strong focus on environmental sustainability. Lastly, South Africa leads in Africa with 12 articles published, possibly due to its significant population and relatively developed status within the continent. However, it is worth noting that the publication output alone is not a comprehensive measure of a country's contribution to the advancement of knowledge in this field. These countries could still be conducting valuable research and making significant contributions to the practical application of biogranulation technology for wastewater treatment in their respective regions. Nonetheless, increasing research output in these countries could potentially lead to more sustainable and cost-effective solutions for wastewater treatment, which would have significant benefits for the environment and public health (Wang et al. 2018; Tan et al. 2021).

The Top 10 most contributing countries in the field of biogranulation for wastewater treatment from 1992 to 2022 are provided in **Table 2**. China being the most prolific contributor to research has a total of 21310 citations and an H-index of 73. The United States follows behind with 5608 citations and an H-index of 46. The remaining top ten countries have made substantial contributions to the field. These countries are generally recognized as developed nations due to their high levels of economic development, industrialization, and technological advancement. In addition, these countries have established research institutions and receive ample funding, which can positively impact their research output and citation impact. **Table 2** also outlines the most cited research papers from the top ten contributing countries in the field. These papers share a common focus on various aspects of wastewater treatment and biological processes, including topics such as anoxic ammonium oxidation (van der Star et al. 2007; Jin et al. 2013), granular sludge (Yilmaz et al. 2008), pharmaceuticals and personal care products removal (Yang et al. 2011), and microbial activity balance (Vlaeminck et al. 2010). They explore different aspects of biodegradation, biosorption, and the performance of advanced treatment systems, such as UASB reactors and sequencing batch reactors, in achieving nitrification, denitrification, and nutrient removal (Hwu et al. 1998; Hawari and Mulligan 2006; Yi et al. 2006; Tang et al. 2011).

Fig. 3(a) shows the changes in publication output over time starting from 1992 until 2022 for ten leading countries in the field of biogranulation technology for wastewater treatment. China and the United States have consistently been the top two countries in terms of publication output, with China surpassing the United States in recent years. The Netherlands and Japan have also been consistent in their publication output but with lower numbers compared to China and the United States. Other countries, such as Spain, Taiwan, Italy, Canada, Singapore, and Australia have shown some variation in their publication output over time. Some countries have had a steady increase in publications, while others have had a more fluctuating trend. The result suggests that biogranulation technology for wastewater treatment has been a topic of interest for researchers worldwide, with a significant increase in publications in recent years. The data also indicates that China has become a major player in this field, with a substantial increase in publication output. Several potential factors may have contributed to fluctuations or absences of certain countries in the field of biogranulation technology during the 1990s as shown in **Fig. 3(a)**. One significant factor may be differences in the amount of research funding provided by both governments and private organizations, the strength of research networks and collaborations between institutions (Tan et al. 2021). Countries with stronger research networks and collaborations may have had greater success in developing and applying biogranulation technology.

Fig. 3(b) displays the number of citations for the top ten leading countries in the field of biogranulation technology between 1992 and 2022. The data shows that China has been the leading country in terms of citations in biogranulation technology since 2013, with an increasing trend over the years. In 2022, China had the highest number of citations with 5363. The United States has been the second-leading country in terms of citations, but the gap between China and the United States has been increasing since 2013. In 2022, the United States had 954 citations, which is much lower than China's 5363. The Netherlands and Japan have consistently been among the top four leading countries in terms of citations, with the Netherlands having the highest number of citations in 2015 with 606, and Japan has the highest number of citations in 2011 with 131. Spain, Taiwan, Italy, Canada, Singapore, and Australia have all had varying levels of citations over the years, but none of them has consistently been among the top four leading countries. **Fig. 3(b)** also shows that the number of citations for all the countries has been increasing over the years, with China having the most dramatic increase in citations. This could be due to the increasing investment in research and development in China and the country's efforts to become a global leader in science and technology (Chen et al. 2015; Omoregie et al. 2022). The other countries have also been investing heavily in research and development, which is reflected in the increasing number of citations. The performance of these countries as shown in **Fig. 3(b)** could be an indication of the potential impact of their research on biogranulation technology for wastewater treatment. Through their research, these leading countries may be able to identify new processes, technologies, or materials that can be used to treat wastewater more efficiently and effectively. This could lead to the development of more sustainable and cost-effective solutions for wastewater treatment, which would have significant benefits for the environment and public health.

A network visualization map of co-authorship analysis of countries was developed through the VOSviewer program as shown in **Fig. 4**. The map displays 69 countries, which are spread across 6 clusters representing different continents. Each cluster is represented by a different colour. Upon analysis of the map, it was found that China has the highest total link strength of 287, with 34 links to other countries, including Malaysia, France, Singapore, Nigeria, Sri Lank, Australia, Germany, Canada, and Qatar. China's strongest collaborations were found to be with Taiwan (31 link strength), Japan (37 link strength), the United States (48 link strength), and Canada (15 link strength). The United States was the second-highest country in total link strength, with a score of 137. However, it had more linkages to other countries (37) than China. The findings suggest that China and the USA are the primary scientific hubs for research collaborations and investigations in the field of biogranulation technology. This has led to an increase in funding for research, development, and innovation in research for wastewater treatment (Guleria and Chakma 2023).

3.3. Top prolific authors in the field

This analysis recognizes the authors who have made significant contributions to the field over the past three decades through their extensive research. **Table 3** lists the top 10 most prolific authors in the field of biogranulation for wastewater treatment from 1992 to 2022. At the forefront of this list, Jin Rencun from Hangzhou Normal University takes the lead with 40 publications and 1624 citations, achieving an H-index of 25. Following closely is Lee Duu-Jong from the City University of Hong Kong, securing second place with 39 publications, 1472 citations, and an H-index of 23. Notably, van Loosdrecht Mark C.M. from the Delft University of Technology also has 39 publications, with an impressive 4080 citations, earning the highest H-index on the list at 28. While Jin Rencun holds the record for the highest number of articles, it is evident that publications by van Loosdrecht Mark C.M. have garnered greater visibility and interest among scholars in the field. The other esteemed authors in the top 10 include Tay Joohwa, Yu-You Li, Peng Yongzhen, Mosquera-Corral Anuska, Campos Jose Luis, Zheng Ping, and Yu Hangqin, all of whom have made notable contributions to this field. Furthermore, the data presented in **Table 3** reveals that the top 10 prolific authors in this field are associated with research institutions in five countries, namely, China, Hong Kong, the Netherlands, Canada, and Spain.

The articles listed in **Table 3** for the top prolific authors all pertain to biogranulation technology, with the common goal of improving the efficiency and effectiveness of wastewater treatment. These papers share a common focus on different aspects of wastewater treatment and microbial processes, including the ANAMMOX process (Tang et al. 2011; Jin et al. 2013), aerobic granules (Lv et al. 2014), biodegradation of specific compounds (Yi et al. 2006), degradation of phenol (Ke et al. 2004), microbial community structures (Cao et al. 2016), and treatment processes such as the CANON process (Vázquez-Padín et al. 2009) and sequencing batch reactor (Ni et al. 2009). They contribute to the understanding of various treatment methods and highlight the importance of microbial communities and granulation mechanisms in wastewater treatment systems.

Fig. 5(a) shows the number of publications for the top ten prolific authors in the field of biogranulation technology from 1992 to 2022. In the early years (1992-1999), none of the authors had any publications in the field of biogranulation technology. However, starting in 2000, the number of publications increased for some authors. From 2000 to 2007, Jin Rencun and Lee Duu-Jong had the most publications, with some contributions from Tay Joohwa. From 2008 to 2010, the number of publications for Lee Duu-Jong increased significantly, while Tay Joohwa also contributed significantly. From 2011 to 2014, there were contributions from several authors, including van Loosdrecht Mark C.M., Mosquera-Corral Anuska, and Campos Jose Luis. In 2015, Lee Duu-Jong, Tay Joohwa, and van Loosdrecht Mark C.M. were the most prolific authors. In the following years, from 2016 to 2022, the number of publications increased for several authors, including Yu-You Li, Peng Yongzhen, Mosquera-Corral Anuska, Campos Jose Luis, Zheng Ping, and Yu Hangqing. Among them, Yu-You Li, Peng Yongzhen, and Zheng Ping had the most publications in recent years. The fluctuations in publication output for these authors may have been caused by various factors. One possible factor is the availability of funding for research, which can impact the amount of research that can be carried out and subsequently published (Guleria and Chakma 2023). Another factor could be the level of interest in biogranulation technology within the scientific community and changes in the academic landscape (i.e., the emergence of new research groups and collaborations) which may have fluctuated over time.

Fig. 5(b) illustrates the changes in citation counts over time for the top ten most prolific authors in the field of biogranulation technology from 1992 to 2022. The results indicate that the number of citations has increased significantly over time for most of the authors. Jin Rencun, Lee Duu-Jong, van Loosdrecht Mark C.M., and Tay Joohwa are consistently among the most cited authors in the field, with steadily increasing citation counts from 1992 to 2022. Yu-You Li, Peng Yongzhen, Mosquera-Corral Anuska, Campos Jose Luis, Zheng Ping, and Yu Hangqing also show a general trend of increasing citation counts, although their counts are generally lower than the top four authors. The data also suggests that certain years saw a particularly significant increase in citations for some authors. For example, 2013 and 2014 saw a large increase in citations for Jin Rencun and Lee Duu-Jong, while 2015 and 2016 were particularly strong years for van Loosdrecht Mark C.M. and Tay Joohwa. Several factors could have influenced the changes in citations for the top ten prolific authors in the field of biogranulation technology over time. The impact of individual researchers within their respective, the availability of funding, and resources may have also contributed to changes in citation patterns over time (Guleria and Chakma 2023). If a researcher made significant contributions to the field, they may have attracted more attention and citations. Collaborations with other influential researchers in the field could also lead to more citations for individual authors.

A network visualization map developed through the VOSviewer program for co-authorship analysis is shown in **Fig. 6**. The map displays 695 authors who are distributed across 27 clusters. Upon analysis of the map, it was found that Li Jun (identified as Li J. on VOSviewer) from Zhejiang University of Technology in Hangzhou, China has the highest total link strength of 187. Li Jun has 110 links with other authors in the field, including Wang Yayi (identified as Wang Y. on VOSviewer) from Tongji University in Shanghai, China with 6 documents, Chen Hui (identified as Chen H. on VOSviewer) from TaiZhou University in Linhai, China, Li Xiyao (identified as Li X. on VOSviewer) from Beijing University of Technology in Beijing, China with 6 documents, and Sellamuthu Balasubramanian (identified as Sellamuthu B. on VOSviewer), from Centre Armand-Frappier Santé Biotechnologie in Laval, Canada with 4 documents. The second author with the highest link strength according to **Fig. 6** is Liu Yang (identified as Liu Y. on VOSviewer) from the University of Alberta in Edmonton, Canada, with a link strength of 199. Liu Yang has 109 links, including Guo Jianbo (identified as Guo J. on VOSviewer) from TaiZhou University in Linhai, China with 3 documents, Wang Jixiang (identified as Wang J. on VOSviewer) from the University of Tsukuba in Tsukuba, Japan with 5 documents, and Zhang Meng (identified as Zhang M. on VOSviewer) from the College of Environmental and Resource Sciences in Hangzhou, China with 6 documents.

3.4. Top performing institutions in the field

Table 4 shows the top 10 institutions that have made significant contributions to the field of biogranulation for wastewater treatment, based on their publication output, citations, and H-index from 1992 to 2022. Harbin Institute of Technology in China has the highest number of publications (104), followed by the Ministry of Education China (84), and Delft University of Technology in the Netherlands (82). However, Delft University of Technology has the highest number of citations (7164) and the highest H-index (45), indicating that their research was significantly impacted in the field. The result indicates that Chinese institutions dominate the list with six of the top ten institutions being in China. This suggests that China has been an active contributor to research in this field over the years. The other institutions listed in **Table 4** are in the Netherlands and Singapore.

The articles listed for the leading institutions the field share a common focus on various aspects of wastewater treatment (i.e., high-strength wastewater, synthetic wastewater, and municipal wastewater), including the characterization of microbial community structures (Li et al. 2005; Cao et al. 2016; Wang et al. 2020), startup experiences of different reactors (van der Star et al. 2007; Tang et al. 2011), biodegradation of specific compounds (p-nitrophenol) (Yi et al. 2006), performance evaluation of treatment system (Pan et al. 2016), and the impact of sulfide inhibition (Jin et al. 2013). They contribute to the understanding of different treatment processes, the role of microbial communities, and the removal efficiency of contaminants in wastewater treatment plants. While some articles examined laboratory-scale experiments, few others carried out pilot-scale or full-scale biogranulation experiments (van der Star et al. 2007; Ni et al. 2009).

Fig. 7(a) displays the publication output of the top 10 institutions in the field of biogranulation for wastewater treatment from 1992 to 2022. After analyzing the data, it is clear that the Harbin Institute of Technology, the Ministry of Education China, and the Delft University of Technology have consistently published in this field since the 1990s. Moreover, there has been a noticeable increase in their publication output in recent years. In comparison, Beijing University of Technology and Tongji University had fewer publications in the early years, but they have steadily increased their research output in the last decade. These two institutions have experienced a significant increase in publications in the past few years. Although Nanyang Technological University, Chinese Academy of Sciences, and Zhejiang University have had fluctuations in their publication output over the years, they still maintained a consistent presence in this field. Hangzhou Normal University has also been publishing but with fewer publications compared to other institutions. Finally, the University of Science and Technology of China had been actively publishing in this field until 2019, after which their publication output dropped significantly. The result in **Fig. 7(a)** indicates the growth and competitiveness of these institutions in research related to biogranulation for wastewater treatment.

Fig. 7(b) displays the citation output of the top 10 institutions in the field. The Harbin Institute of Technology is the top-performing institution with a total of 3,178 citations over three decades. The Ministry of Education China is the second most contributing institution with a total of 1,496 citations, followed closely by the Delft University of Technology with 6 citations less (1,490 citations). The remaining institutions in the top 10 have a total citation output ranging from 596 (University of Science and Technology of China) to 1,675 (Nanjing University). However, the citation output trend of Beijing University of Technology, the Chinese Academy of Sciences, Hangzhou Normal University, and the University of Science and Technology of China varied more throughout the years. Some of these institutions experienced years with high citation output followed by years with lower citation output. The data presented in **Fig. 7(b)** shows that the top institutions in the field of biogranulation for wastewater treatment have been actively contributing to the field. The citation output for these institutions has shown a generally increasing trend over the years, indicating the importance and impact of their research in the field.

3.5. Top performing journals in the field

According to Scopus online data, the articles in the field of biogranulation for wastewater treatment from 1992 to 2022 were published in 144 different journals. **Table 5** displays the top 10 journals with the most productivity in this field. The most productive journal is *Bioresource Technology*, with 249 articles published, which has an impressive citation count of 9851 and an H-index of 60. The second most productive journal is *Water Research*, with 192 articles published, which has the highest citation count among all the journals in the list with 14277 citations and an H-index of 72, indicating that it has many highly cited articles. The third most productive journal is *Water Science and Technology*, with 102 articles published, a citation count of 2466, and an h-index of 26. Science of the *Total Environment* and *Chemosphere* rank fourth and fifth, respectively, with 78 and 75 articles published. Both have comparatively high citation counts and h-indices compared to other journals on the list. The other five journals on the list are *Chemical Engineering Journal*, *Journal of Hazardous Materials, Environmental Technology United Kingdom, Applied Microbiology* and *Biotechnology,* and *Biochemical Engineering Journal*.

The papers listed in **Table 5** share a similar focus on various aspects of wastewater treatment, including the performance evaluation of treatment systems (Schwarzenbeck et al. 2005; Ghangrekar and Shinde 2007), startup experiences of reactors (van der Star et al. 2007), selection of microbial organisms for sludge stability improvement (de Kreuk and van Loosdrecht 2004), application of bacteria for effluent purification (Janssen et al. 2009), nitrogen removal efficiency analysis (Cho et al. 2010), denitrification, and phosphorus removal (Wang et al. 2018), biosorption studies (Gao et al. 2010), characteristics of granules, and roles of extracellular polymeric substances in granulation processes (Tay et al. 2002; Ni et al. 2015). These articles contribute to the understanding of different treatment approaches, microbial communities, and the optimization of wastewater treatment processes.

Table 6 presents data on the performance metrics of the top 10 most productive journals in the field, based on the Scopus database. The journals cover various subject areas, including Environmental Engineering, Waste Management and Disposal, Bioengineering, Renewable Energy, and Sustainability and the Environment, among others. Elsevier is the most dominant publisher, with seven journals in the top 10 list. The remaining publishers include Taylor & Francis, IWA Publishing, and Springer Nature. The CiteScore, SJR, and SNIP are performance metrics used to evaluate the impact and influence of journals (Omoregie et al. 2022). Among the top 10 journals, *Water Research* has the highest CiteScore, SJR, and SNIP values of 18, 2.806, and 2.499, respectively. *Journal of Hazardous Materials* and *Science of the Total Environment* also scored high in these metrics. The quartile ranking, which indicates the position of a journal within its subject category based on its performance metrics, shows that all the journals in the top 10 list are highly regarded in their respective subject areas, with five in the first quartile and five in the second quartile.

Fig. 8(a) displays the publication output of the top ten journals in the field of biogranulation technology between 1992 and 2022, representing the number of articles published annually in each respective journal. Over the analyzed period, *Bioresource Technology* has consistently remained the top-performing journal, with a steady increase in the number of articles published each year. A total of 361 articles have been published *in Bioresource Technology* from 1992 to 2022. *Water Research* and *Science of the Total Environment* have also been consistent performers, publishing over 200 articles in this field during the same time frame. While *Chemosphere, Chemical Engineering Journal*, and *Environmental Technology United Kingdom* have published a significant number of articles in this field, their output has been more variable over time. *Journal of Hazardous Materials* and *Biochemical Engineering Journal* have published fewer articles in this field compared to the other journals. In recent years, the number of articles published in this field has increased across journals, with several journals publishing a record number of articles in 2022. This trend indicates a growing interest in biogranulation technology, and more researchers are focusing their efforts on studying this area.

The publication output of the top ten performing journals in the field of biogranulation technology between 1992 and 2022 has shown fluctuations that may be attributed to several factors. One possible factor is the emergence of new technologies and methodologies, which can influence research directions and subsequently affect publication output in these journals. Changes in funding priorities could also shift the focus of researchers, leading to changes in the topics being published. Additionally, changes in editorial policies or the editorial board of these journals may have an impact on the publication output. Societal or environmental concerns could also play a role, as increased awareness of the need for sustainable technologies may have influenced research direction and contributed to changes in publication output. Ultimately, multiple factors could contribute to the fluctuations observed in the publication output of these journals over time.

Fig. 8(b) presents the citation output over time for the top ten performing journals in the field of biogranulation technology from 1992 to 2022. *Bioresource Technology* and *Water Research* are the two highest-performing journals in this field, as evidenced by the steady increase in their citation output over time. Although *Bioresource Technology* had zero citations in 1992, it received 2012 citations by 2022, while *Water Research* received zero citations in 1992 but had 2256 citations by 2022. *Water Science* and *Technology*, and *Science of the*

Total Environment also experienced a slow and steady increase in their citation output, but it was still lower than the top two journals. *Chemosphere* and *Chemical Engineering Journal* initially received few citations, but their citation output increased significantly after 2000. Although the *Journal of Hazardous Materials* had a slow start, its citation output rapidly increased after 2009. *Environmental Technology United Kingdom*, *Applied Microbiology and Biotechnology*, and *Biochemical Engineering Journal* had lower citation output over time, with *Applied Microbiology and Biotechnology* receiving the least citations among the ten journals listed. Several factors can contribute to the fluctuation of publication and citation output in scientific journals, such as the emergence of new research topics, the adoption of new research methodologies or techniques, and interest and investment in a particular research field (Ilmasari et al. 2022). Changes in the number of publications and the level of competition within a field can also affect citation output (Purba et al. 2022). Researchers may cite more papers to establish the novelty and significance of their research, which can impact citation patterns.

According to the Scopus database, the published articles were classified across 21 different subject areas. **Supplementary information, Table S2** presents the top 10 subject areas in the field of biogranulation for wastewater treatment between 1992 and 2022. Environmental Science has the highest number of articles with a total of 1,415 publications, indicating a significant focus on research related to the environment. Other prominent subject areas include Chemical Engineering with 621 articles, Biochemistry, Genetics, and Molecular Biology with 264 articles, and Energy with 333 articles. There is also representation from various disciplines such as Chemistry, Engineering, Immunology and Microbiology, Medicine, and Physics and Astronomy, among others. However, some subject areas have relatively fewer publications, such as Health Professions, Economics, Econometrics and Finance, and Neuroscience, suggesting a comparatively lower level of research activity in those fields, but still represent important contributions to the field of biogranulation for wastewater treatment. The articles listed in **Supplementary information, Table S2** for the top 10 subject areas have a similar focus on different aspects of wastewater treatment and anaerobic processes. They explore topics such as startup experiences of reactors for anoxic ammonium oxidation (van der Star et al. 2007), the performance evaluation of membrane-less microbial fuel cells for wastewater treatment (Ghangrekar and Shinde 2007), anaerobic digestion systems (Lettinga 1995), microbial population dynamics in granular sludge (Szabó et al. 2017), and the application of advanced treatment methods for wastewater reclamation (Petala et al. 2006). Additionally, some papers specifically investigate the growth of anammox bacteria on pretreated municipal wastewater (Lotti et al. 2014) and the impact of aggregate size and architecture on microbial activity in partial nitritation and anammox processes (Lettinga 1995; Vlaeminck et al. 2010). Collectively, these papers contribute to the understanding of anaerobic treatment processes, microbial communities, and the advancement of wastewater reclamation techniques.

3.6. Trending author keywords

Authors must select their keywords with great care to precisely reflect the main idea of their research. Additionally, these keywords can be used to identify the current research trends in a specific field. To better understand the connection between these keywords, it is important to investigate their interlinkages. **Fig. 9** displays an overlay visualization of author keywords that co-occurs in the field of biogranulation technology for wastewater treatment from 1992 to 2022. Using the VOSviewer program for analysis, the most frequently occurring author keyword is "aerobic granular sludge" with 383 occurrences, total link strength of 442, and 223 links to other keywords. Further analysis using VOSviewer demonstrated that since 2020 some keywords started gaining linkage with "aerobic granular sludge". These keywords include "mainstream wastewater", "carriers", "continuous flow reactor", "full-scale", "calcium phosphate", "machine learning", "sludge morphology", "pollutant removal efficiency", "biofuel", "hydrochar", "greenhouse gas" and "diffusion".

The other keywords, such as "heavy metal", "microbial community diversity", and "total organic carbon" are related to different aspects of the biogranulation technology, indicating that the field is multifaceted and involves many different areas of research. Due to the dense structure of aerobic granules, microorganisms within the granules can cooperate and share their metabolic pathways, enabling the complete degradation of the recalcitrant organic compounds, including heavy metals (Sarma et al. 2017). Furthermore, the co-occurrence of these keywords suggests that there may be some interrelationship or interdependence among them. For example, "aerobic granular sludge" is linked with "anammox" which refers to a specific process of removing nitrogen from wastewater. This connection may indicate that aerobic granular sludge plays a role in the anammox process, or that research into the anammox process often involves the use of aerobic granular sludge (Winkler et al. 2012). The observation that certain keywords have recently become associated with "aerobic granular sludge" indicates an increasing significance of these topics in the realm of biogranulation technology used for treating wastewater. For instance, the use of terms like "mainstream wastewater" and "continuous flow reactor" may suggest a move towards more efficient and uninterrupted wastewater treatment. Similarly, the mention of "machine learning" implies the integration of artificial intelligence for optimizing the biogranulation process. Machine learning through artificial intelligence can be used to develop real-time monitoring systems real life applications, adjust the nitrification and denitrification operating phases and continuous monitoring to maintain optimal biological nitrogen removal (Gao et al. 2011; Zaghloul et al. 2021). Additionally, the incorporation of words such as "biofuel", "hydrochar", and "greenhouse gas" highlights the potential of biogranulation technology to not only treat wastewater but also contribute to renewable energy production and environmental sustainability.

Another frequently occurring author keyword as demonstrated in **Fig. 9** is "anammox" which has 269 occurrences and is linked to keywords such as "granular characteristics", "candidatus kuenenia", and "kinetic model." This suggests that anammox is a prominent topic in the field of biogranulation technology, with researchers interested in its characteristics and modelling. Recent studies have adapted machine learning methods and developed models to simulate the fluctuations in effluent quality, assess the impact on the reactors, and predict the performance (Zaghloul et al. 2021). Another important author keyword was "anaerobic granular sludge" with 142 occurrences, which was linked to keywords such as "groundwater", "micro algae", and "low strength ammonium wastewater." This indicates that research on anaerobic granular sludge focuses on its potential applications in different contexts such as groundwater remediation and microalgae cultivation. The author keyword "microbial community" has 191 occurrences and is linked to keywords such as "aerobic denitrification", "dichlorination", and "microplastic." This suggests that researchers are interested in the microbial community dynamics and their potential role in biogranulation technology, including the degradation of emerging pollutants such as microplastics. The degradation of microplastics is challenging due to their complex characteristics (Yuan et al. 2022). The presence of high concentrations of microplastics can impact the performance of the biogranulation process (Wang et al. 2021). However, the degradation pathway of the microplastics through the biogranulation process remains unclear. Therefore, further research is needed to shed light on this topic.

The author keyword "sequencing batch reactor" has 64 occurrences and is linked to keywords such as "color removal", "palm oil mill effluent", and "high temperature." This indicates that SBR is a commonly used technology in biogranulation research, with researchers interested in its performance under different conditions and for different types of wastewaters. The flexible properties of SBR make it a preferred technology for biogranulation studies. It can exert hydrodynamic shear force by supplying superficial up-flow air velocity, which is crucial for the formation of aerobic granules (Nancharaiah and Kiran Kumar Reddy 2018; Ali et al. 2021). Several studies have investigated the performance of the biogranulation process in treating different types of wastewaters using the SBR system, including palm oil mill effluent (Abdullah et al. 2011; Najib et al. 2017), domestic sewage (Nancharaiah and Kiran Kumar Reddy 2018; We et al. 2021), landfill leachate (Nikolova-Kuscu et al. 2013; Yan et al. 2022), and textile wastewater (Kee et al. 2015).

In addition, the author keyword "extracellular polymeric substances" has 67 occurrences and is linked to keywords such as "dewaterability", "granule formation", and "sulfur cycle." This suggests that researchers are interested in the properties and functions of extracellular polymeric substances (EPS) in biogranulation technology, including their role in granule formation and wastewater treatment. EPS plays a crucial role in the formation of biogranules, as EPS can provide adhesion to the granules, bind bacterial cells tightly together, and enhance the structural stability of the developed granules, thereby enhances the removal performance of the system (Basri et al. 2023). Finally, the author keyword "methanogenesis" has 40 occurrences and is linked to keywords such as "biogranule", "biostimulation", and "fatty acids." This suggests that researchers are interested in the potential for biogranulation technology to produce methane from organic waste, and are exploring ways to optimize the process. These findings suggest that biogranulation technology for wastewater treatment is a complex and multifaceted field of research, with a wide range of topics and applications that researchers are exploring.

3.7. Research area and key directions

The network mapping of research terms in the field of biogranulation technology for wastewater treatment is shown in **Fig. 10**. The VOSviewer program was used to analyze the occurrences of research terms and their links in the network, and the results show several high-frequency research terms and their linked terms. The term “sequencing batch reactor” stands out as the most frequently occurring term (433), with 249 links and 3045 total link strength. It indicates the importance of this technology in the field of biogranulation for wastewater treatment. Some of the research terms which were linked to “sequencing batch reactor” consist of “low temperature”, “retention time”, “ammonia removal”, “effluent”, “pollutant”, “precipitation”, “volatile fatty acid”, “cultivation”, “granulation process”, and “biofilm”. The linked terms indicate the research areas that are focused on improving the performance of sequencing batch reactors. The term “aerobic granulation” is another high-frequency term (339 occurrences), indicating the growing interest in this area of research. The terms linked to “aerobic granulation” are “inhibition”, “mixture”, “diameter”, “response”, “distribution”, “behavior”, “product”, “energy”, “retention time”, and “pressure” The linked terms suggest that researchers are investigating the factors that influence the aerobic granulation process and the ways to optimize it for wastewater treatment. Several factors can inhibit/ influence the granulation process. For instance, it is important to select an appropriate hydraulic retention time to avoid the biomass being flushed out. The cycle time of the SBR system is also important because it serves as hydraulic selection pressure, which promotes the formation of stable granules with fast-settling properties (Wang et al. 2021; Omar et al. 2023).

Other notable high-frequency terms that were identified by the VOSviewer program as shown in **Fig. 10** include “community” with 291 occurrences, “substance” with 273 occurrences, “structure” with 263 occurrences, “upflow anaerobic sludge blanket reactor” with 221 occurrences, “mechanism” with 211 occurrences, “role” with 204 occurrences, and “effluent” with 202 occurrences. These terms indicate the broader themes and areas of research in biogranulation technology. These terms also suggest that researchers are investigating the microbial communities involved in the granulation process, the substances and compounds that affect the process, and the structure and characteristics of the granules. It is interesting to note that the microbial communities present in biogranules can vary depending on different operation parameters and substrate properties (Geng et al. 2022). Moreover, the microbial population within the biogranules may change/ shift when exposed to different carbon sources (Winkler et al. 2012). The identification of the upflow anaerobic sludge blanket reactor as a high-frequency term suggests that this technology is still relevant and widely used in the field of biogranulation for wastewater treatment. The configuration of an upflow anaerobic sludge blanket reactor is ideal for the formation of biogranules due to its gas-liquid-solid separator, which retains the biomass and allows for the upward flow of influent to exert shear force and promotes the development of biogranules (Wang et al. 2021; Omar et al. 2023). The network mapping of research terms in the field of biogranulation technology for wastewater treatment provides a useful overview of the research trends and patterns in this field. The identified high-frequency terms and their linked terms can guide researchers to focus on specific areas of research and explore new avenues for improving the performance of biogranulation technology for wastewater treatment.

Fig. 11 shows a word cloud presenting the most significant key terms based on their frequency of appearance in articles related to the field of biogranulation technology for wastewater treatment from 1992 to 2022. The size of each term in the word cloud is proportional to its frequency, indicating the importance and prevalence of these terms in the literature. The most frequently occurring key terms include "wastewater treatment" and "sewage," with 1757 and 1589 occurrences, respectively. This highlights the primary focus of the research on utilizing biogranulation technology for the treatment of wastewater and sewage, which are critical areas in environmental management. Other key terms closely related to the wastewater treatment context are "nitrogen," "denitrification," "sludge," "chemical oxygen demand," "phosphorus," and "ammonia." These terms underline the significance of nitrogen and phosphorus removal processes, such as denitrification and nitrification, in biogranulation systems. Additionally, "bioreactor" and "bioreactors" with 1113 and 918 occurrences, respectively, demonstrate the prevalence of using bioreactors in implementing biogranulation technology for wastewater treatment.

The word cloud also emphasizes the importance of "granulation" and "granular materials" (739 and 731 occurrences, respectively), which reflects the core concept of biogranulation, involving the formation of dense and firm granules. Furthermore, terms like "microbial community," "biomass," and "bacteria" (with 706, 687, and 578 occurrences, respectively) indicate the focus on the diverse microbial populations responsible for pollutant degradation and granule formation in the biogranulation process. Regarding process-related terms, "activated sludge," "aerobic granular sludge," and "anaerobic digestion" (with 510, 297, and 321 occurrences, respectively) highlight the usage of these biological processes in biogranulation systems. "Anammox" and "anoxic conditions" (with 253 and 238 occurrences, respectively) point to the significance of anaerobic ammonium oxidation and anaerobic growth conditions in achieving efficient nitrogen removal.

Other notable terms in **Fig. 11** include "pollutant removal," "methane," "biodegradation," "particle size," "metabolism," "effluents," "biofilm," and "temperature." These terms represent various factors and processes involved in the biogranulation technology for effective wastewater treatment. The word cloud provides a comprehensive overview of the key themes and research areas related to biogranulation technology for wastewater treatment. The prominence of specific terms indicates the significance of certain processes, microbial communities, and operational parameters in optimizing the biogranulation process for efficient pollutant removal and sustainable wastewater management. The insights from this word cloud analysis can guide future research and development in this field, facilitating advancements in biogranulation technology for more effective and environmentally friendly wastewater treatment solutions.

4. Prospects, challenges, and future direction in Biogranulation Technology

Biogranulation technology has become increasingly popular for its efficiency in removing pollutants, such as carbon, nitrogen, and phosphorus from wastewater. The biogranules formed during biogranulation have a dense and firm structure that allows them to handle high organic loading rates and settle easily (Nuid et al. 2023). Moreover, their surface hydrophobicity promotes aggregation and the formation of larger granules, comprising millions of microorganisms with diverse compositions, enabling the degradation of various organic compounds and ensuring effective treatment of different wastewater compositions (Ali et al. 2021). The process of biogranulation in biological wastewater treatment involves multiple phases and mechanisms depicted in **Fig. 12**, lasting from 0 to 200 days or more (Omar et al. 2023). However, the initial stage is critical as it influences the characteristics and stability of matured (Haaksman et al. 2023).

A key mechanism during biogranulation is the formation of extracellular polymeric substances (EPS), composed of polysaccharides, proteins, and organic compounds, which provide mechanical stability to the granules and protect microorganisms from adverse conditions (Giesen et al. 2013). Manipulating EPS production through various strategies as depicted in **Supplementary Information, Fig. S1, and Table S3**, includes characterizing and quantifying EPS, optimizing operational parameters, and exploring microbial communities' role, can improve the functionality and stability of biogranulation systems for more effective wastewater treatment (Wang et al. 2022). **Table 7** summarizes different research studies that has successfully used biogranulation technological process to treat various wastewaters. These studies investigate various aspects, including biogranule properties, pollutant removal capabilities, and microbial communities. Real municipal wastewater analysis is essential for assessing performance in large-scale treatment plants with more complex and variable compositions. Comparing biogranulation technology with conventional methods, like the ponding system and conventional activated sludges, reveals its higher pollutant removal efficiency, cost-effectiveness, and positive environmental impact (Pronk et al. 2015; Omar et al. 2020). Though biogranulation technology shows great promise, its implementation at large scales face challenges, such as high capital costs and long startup periods. Continued research and innovation are necessary to overcome these hurdles and fully realize the potential of this technology. As the focus on sustainability grows globally, biogranulation technology is poised to revolutionize wastewater management and contribute to achieving sustainable development goals.

For future direction, while synthetic wastewater has been extensively used to investigate granular properties, pollutant removal capabilities, and microbial communities, there is a need to optimize its composition and concentration to better simulate real-world conditions. The analysis of real municipal wastewater provides an opportunity to assess the scalability and performance of granule-based large-scale treatment plants in diverse settings (Ekholm et al. 2022). Contrasting studies on the biogranulation process at different organic loading rates yield valuable information for optimizing operational strategies in biogranulation reactors. (Szabó et al. 2017; Suryati et al. 2021; Nuid et al. 2023). Further research should aim to deepen the understanding of granulation mechanisms under various loading conditions, optimizing granule formation, and improving settling velocities to enhance treatment efficiency. Additionally, investigating the impact of specific components, such as nitrate and algae, on the formation of anaerobic and aerobic granular sludge, respectively, can shed light on underlying mechanisms and metabolic pathways. This knowledge will be instrumental in optimizing granule formation and understanding microbial interactions in the presence of these components (Xiao et al. 2022). Moreover, the application of biogranulation technology in treating synthetic wastewater highlights the potential for integrating physicochemical and biological approaches. Future research could also explore the synergistic effects of different treatment techniques, assess the long-term stability of the biogranulation process, and evaluate the potential for resource recovery from industrial and municipal wastewater. These research directions will further enhance the efficiency and applicability of biogranulation technology in wastewater treatment. Bridging the gap between laboratory-scale studies and large-scale treatment plant applications will ensure the scalability and practicality of biogranulation technology across diverse settings.

The application of machine learning techniques, specifically Artificial Neural Networks (ANN) and Response Surface Methodology (RSM), shows great potential for optimizing biogranulation technology in the treatment of municipal and industrial wastewater (Mandal et al. 2020; Dragoi et al. 2021; Hakke et al. 2023). ANN can be employed to create models that predict intricate relationships between different process parameters and their effects on biogranulation performance. By inputting historical data encompassing wastewater composition, environmental conditions, and granulation outcomes into the ANN model, researchers can gain valuable insights into the factors influencing the efficiency of the biogranulation process. This predictive capability enables real-time adjustments and fine-tuning of operational parameters to achieve the best granule formation and pollutant removal outcomes. Adoption of ANN model in future biogranulation system, can help researcher studies numerous wastewater including those derived from agro-based biomass effluent that are produced during the processing of agricultural materials or organic residues especially at large-scales (Amusa et al. 2021a, b). Moreover, RSM offers a statistical approach for optimizing the biogranulation process by efficiently exploring the experimental design space. This method significantly reduces the number of required experiments, thus saving time and resources, all while yielding robust and reliable results (Kumar Tiwari et al. 2007; Faraji et al. 2022). By integrating ANN and RSM in future studies, researchers can fully leverage the potential of biogranulation technology, maximizing its efficacy in treating municipal and industrial wastewater. This integrated approach not only improves pollutant removal capabilities but also contributes to the overall sustainability and cost-effectiveness of wastewater treatment processes, effectively addressing the mounting challenges of environmental pollution and waste management.

Limitations of the Study

This study provides quantitative analyses of the research trends in biogranulation technology for wastewater treatment from 1992 to 2022. However, it is important to note that the data collection was limited to articles containing specific keywords such as "biogranulation," OR "granular sludge process," OR "microbial granulation," OR "biogranules," OR "granulation technology" AND "wastewater treatment" in the titles, abstracts, and author keywords. Therefore, articles without these keywords were not included in the analysis. Additionally, the study focused solely on research articles within the Scopus database, and it may be beneficial to compare or select data from other databases. To further address the limitations of this study, future research can expand keyword inclusion, include multiple databases, consider various article types, incorporate qualitative analysis, and extend the time range to provide a more comprehensive understanding of biogranulation technology for wastewater treatment.

Conclusion

The field of biogranulation technology for wastewater treatment has experienced significant growth, as evident from the increasing number of publications over time. The cumulative publication output surged from 4 articles in 1992 to an impressive 1703 articles by 2022. China emerges as the leading country in terms of publication output, closely followed by the United States, the Netherlands, and Japan. Several other countries, including Spain, Taiwan, Italy, Canada, Singapore, and Australia, have also made noteworthy contributions to the field. A comprehensive analysis further identifies the top authors, institutions, and journals in this area. Jin Rencun emerges as the most prolific author, and the Harbin Institute of Technology and Delft University of Technology stand out as top contributing institutions. Among journals, Bioresource Technology leads in productivity, while Elsevier stands out as a dominant publisher. Among the author keywords, "aerobic granular sludge" takes center stage in biogranulation technology for wastewater treatment. Analysis using the VOSviewer program reveals that "sequencing batch reactors" and "aerobic granulation" appear with the highest frequency in research terms. Conversely, R-Studio software analysis points to "wastewater treatment" and "sewage" as the primary research focus in using biogranulation for treating wastewater and sewage, which are critical aspects of environmental management. These findings significantly contribute to the knowledge base and can serve as a valuable reference for inspiring further advancements in this promising area of research. The remarkable growth and global interest in biogranulation technology showcase its potential as a transformative solution in wastewater treatment, providing crucial insights for researchers and practitioners working towards more efficient and sustainable environmental management.

Author contributions

Abiodun Abdulhameed Amusa, Armstrong Ighodalo Omoregie, and Mansur Alhassan were responsible for gathering metadata, conducting data analysis, and drafting the initial version of the manuscript. The study was funded by Anwar Johari. Luiza Campos, Chukwuka Christian Ohueri, Tariq Ouahbi, and Oluwapelumi Olumide Ojuri participated in reviewing and making revisions to the manuscript. All authors have diligently reviewed and agreed to the final version of the manuscript.

Declaration of Competing Interest

The authors affirm that they do not have any known financial interests or personal relationships that could have potentially influenced the findings presented in this manuscript.

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Data Availability

The corresponding author will provide the data upon request.

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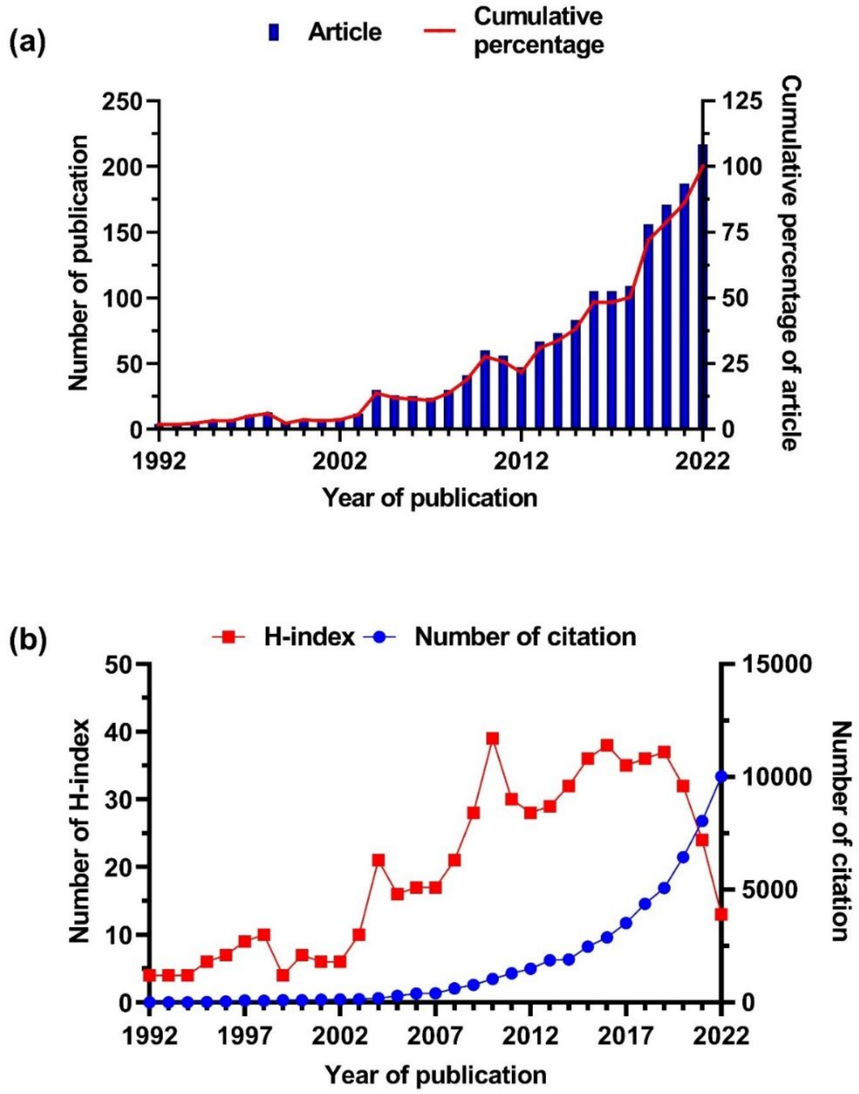

Fig. 1: Overview of publication and citation trends in the field of biogranulation technology for wastewater treatment from 1992 to 2022. (a) the number of articles and their cumulative percentage, and (b) the number citations and the H-index metric.

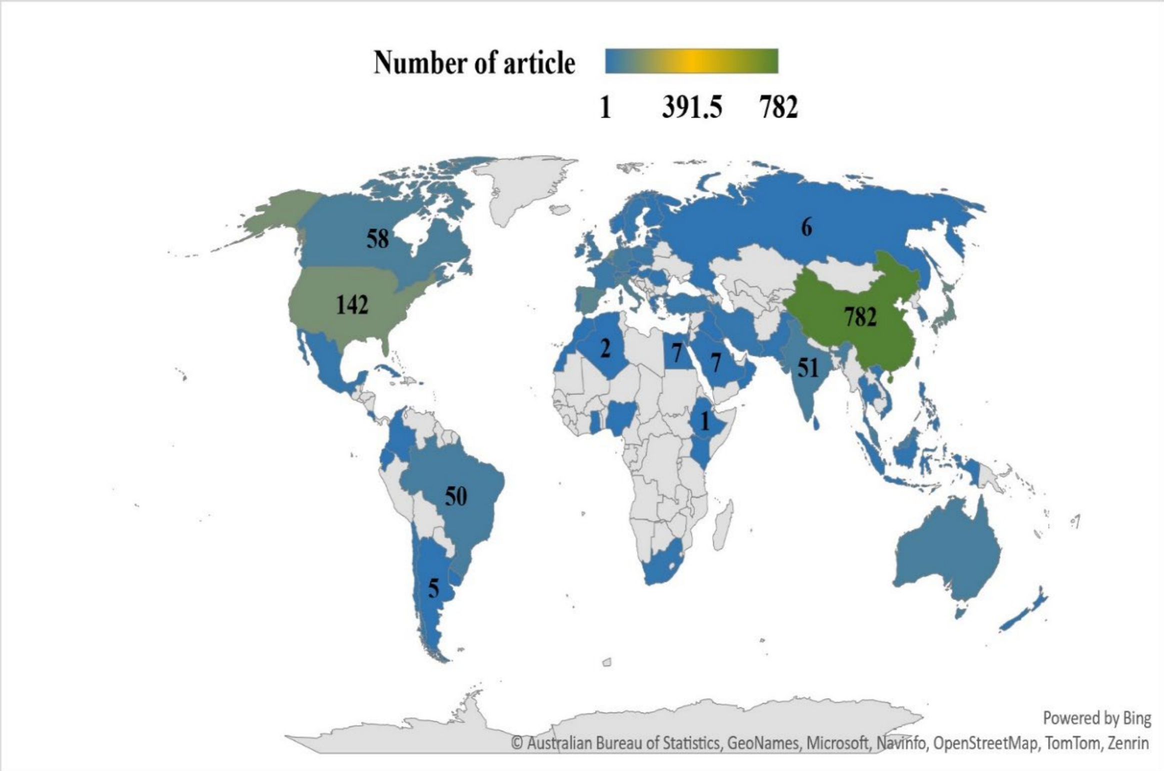

Fig. 2: Global geographical distribution of research on biogranulation technology for wastewater treatment between 1992 to 2022. The colour changes from blue to green represent the number of publications indexed in Scopus database that are attributed to different countries.

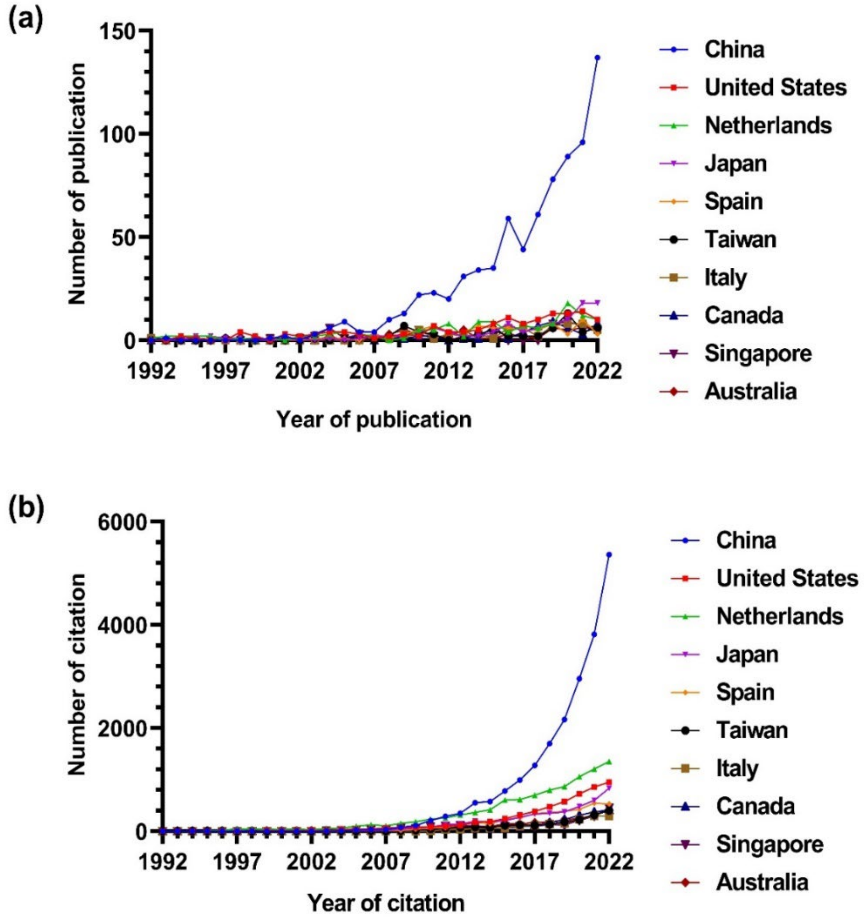

Fig. 3: Contribution of top ten leading countries in the field of biogranulation technology between 1992 to 2022. (A) Number of articles published and (B) annual number of citations.

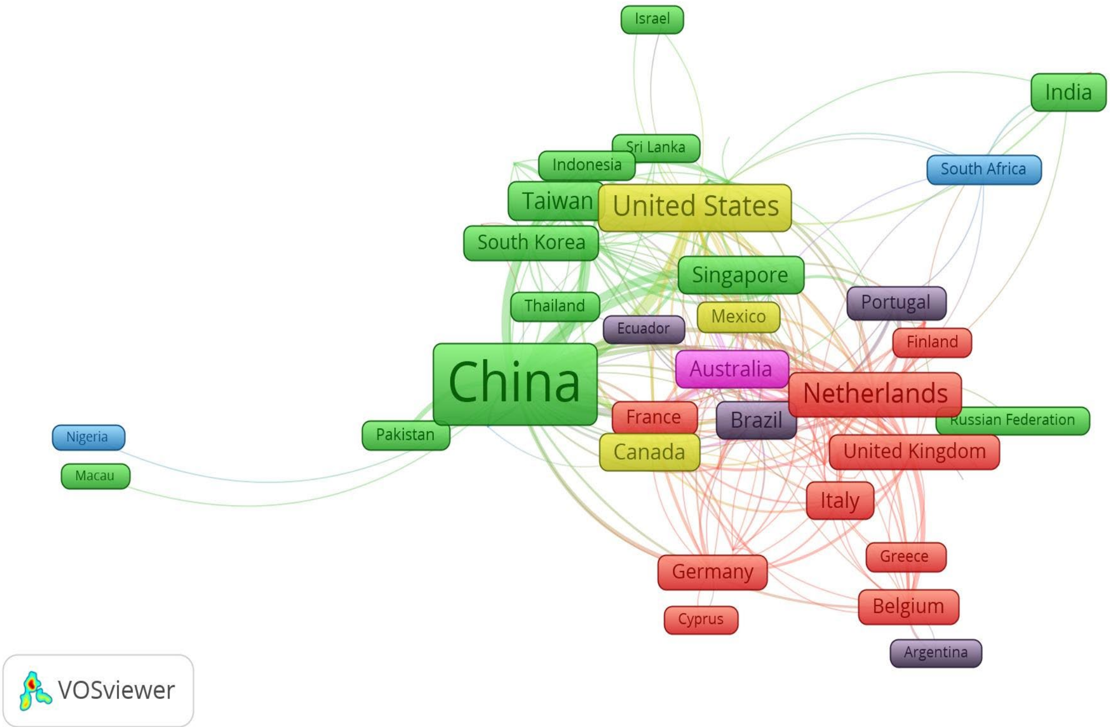

Fig. 4: Network visualization of co-authorship analysis of countries in the field of biogranulation technology for wastewater treatment between 1992 to 2022.

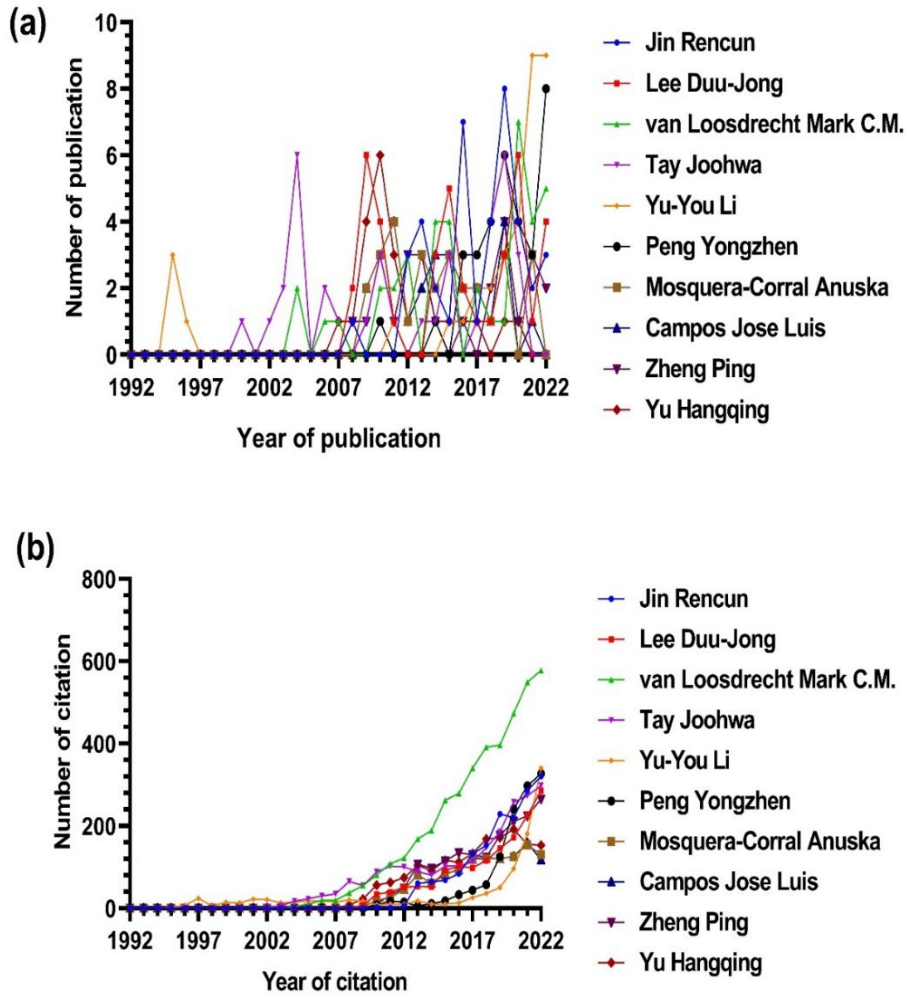

Fig. 5: Top ten prolific authors in the field of biogranulation technology between 1992 to 2022. (A) Number of articles published and (B) annual number of citations.

Fig. 6: Network visualization of co-authorship analysis of authors in the field of biogranulation technology for wastewater treatment between 1992 to 2022.

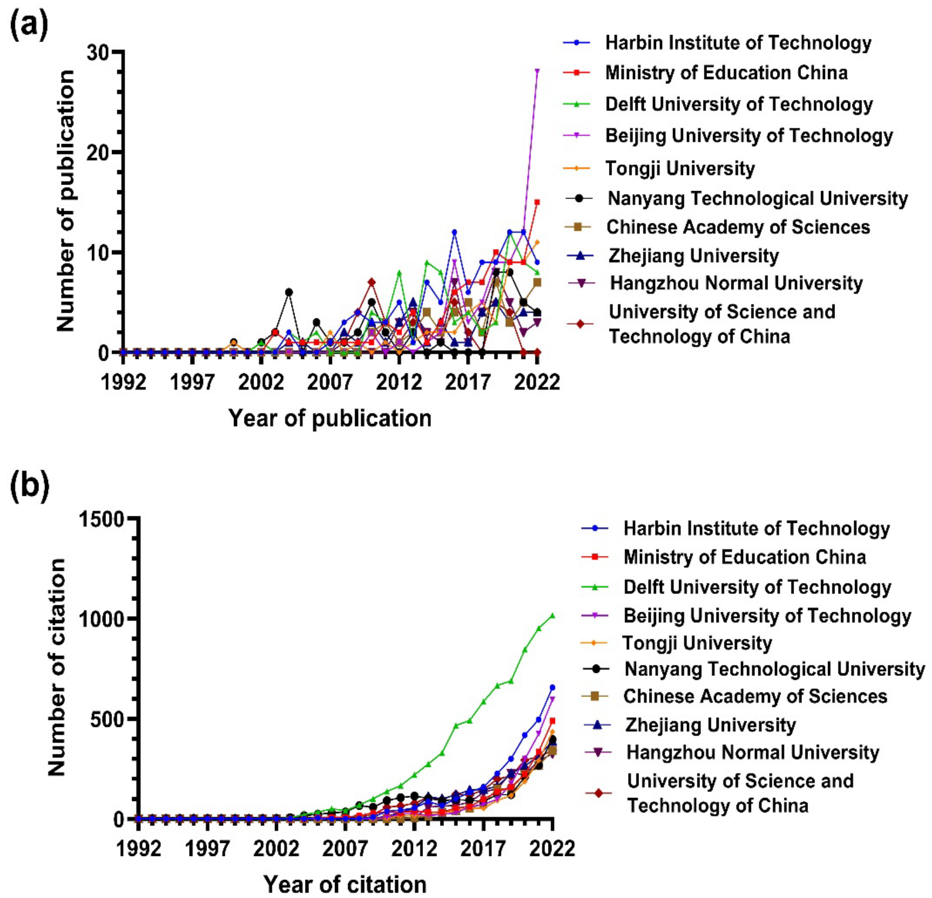

Fig. 7: Top ten institutions in the field of biogranulation technology between 1992 to 2022. (A) Number of articles published and (B) annual number of citations.

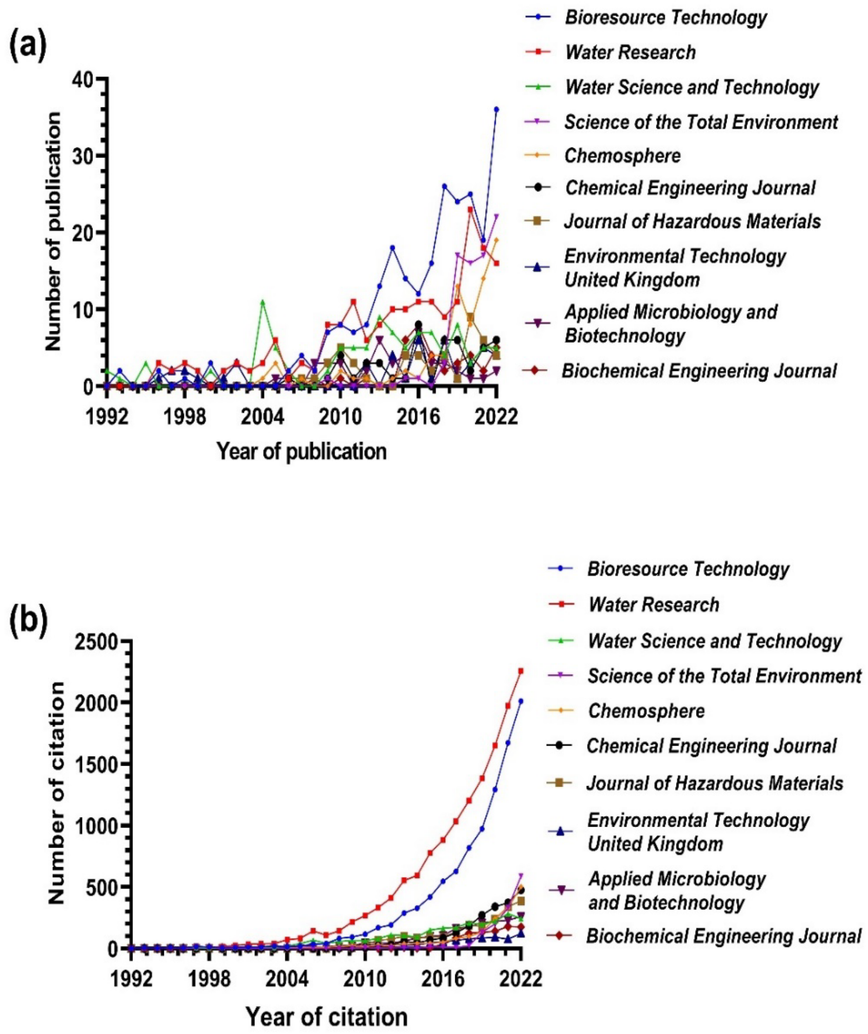

Fig. 8: Top ten performing journals in the field of biogranulation technology between 1992 to 2022. (A) Number of articles published and (B) annual number of citations.

Fig. 9: Overlay visualization of co-occurrence analysis of author keywords in the field of biogranulation technology for wastewater treatment from 1992 to 2022.

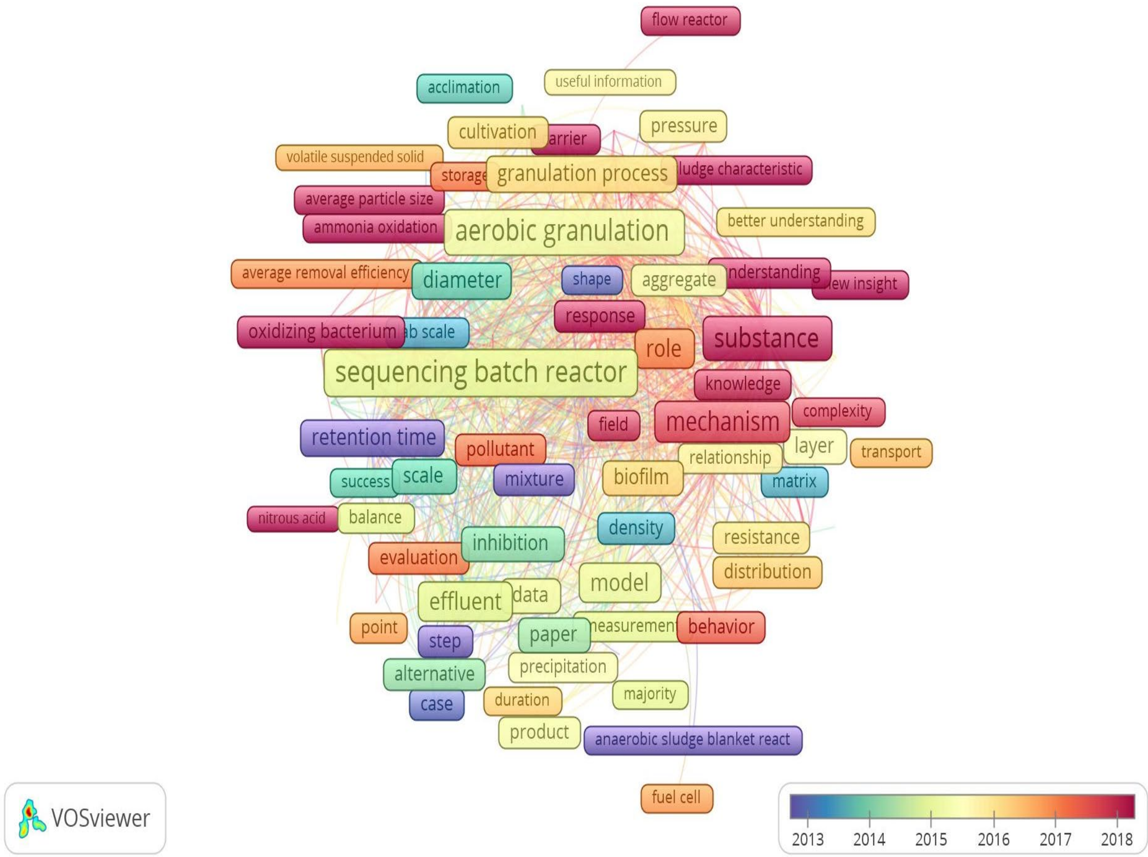

Fig. 10: Network visualization map of the text terms from articles published related to the field of biogranulation technology for wastewater treatment from 1992 to 2022 using VOSviewer software.

Fig. 11: The word cloud showing the most significant key terms based on frequency of their appearance in the articles related to field of biogranulation technology for wastewater treatment from 1992 to 2022. The key terms were generated from text file analysis using R-studio software.

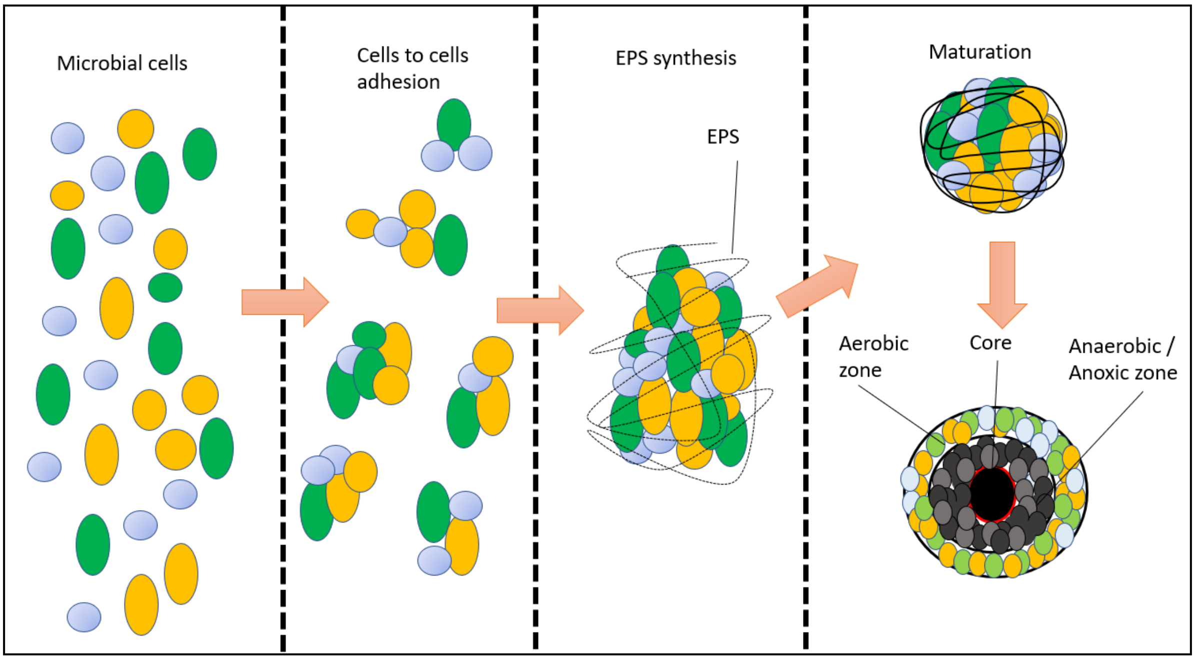

Fig. 12: Illustration depicting various stages of the biogranules formation process.

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Table 1: Summary of several bibliometric articles that previously reported publication trends of biogranulation or areas related to the field.

Title of article	**Main highlight of the study**	**Years covered in scientific database**	**Scientific database used to extract data**	**Selected key terms to search database**	**Visualization software**	**Limitation of the study**	**Reference**
Discovering future research trends of aerobic granular sludge using bibliometric approach	The study analyzed 1203 research articles from the scientific database. The dominant countries in aerobic granular sludge (AGS) research were identified as the Netherlands and China. The study also revealed recent developments involving biochar and algal addition in AGS processes. Additionally, the	1997 to 2020	Scopus	(“aerobic granular sludge” OR “aerobic granul* sludge” OR “aerobic granulation”) OR AUTHKEY (“aerobic granular sludge” OR “aerobic granul* sludge”	VOSviewer program	The limitation of this study is that it only analyzed articles containing specific keywords related to aerobic granular sludge (AGS), potentially excluding relevant articles that did not use those keywords. Additionally, the analysis was limited to articles available in the Scopus database, which may not provide a complete picture.	(Purba et al. 2022)

	application of AGS for antibiotic-containing wastewater treatment and resource recovery showed promise and is expected to expand in the future.			OR “aerobic granulation”)			
Emerging trends of microalgae bio-granulation research in wastewater treatment: A bibliometric analysis from 2011 to 2023	The paper found 250 publications, with China being the most active country in this field. While research mainly focuses on microalgae-bacteria symbiosis for granulation, there is a lack of studies on denser single-species microalgae granules without bacteria for easier harvesting. Furthermore, the effects of organic and	2011 to 2023	Web of Science (WOS), Scopus and Google Scholar	(“Microalgae” AND “Bio-granulation” AND “Harvesting” AND “Wastewater treatment”)	VOSviewer program	the authors did not conduct a comprehensive analysis or report on the subject. Instead, they performed a selective bibliometric review focusing on specific aspects. They aimed to identify research trends in microalgae bio-granulation by reviewing relevant articles, determining the nations contributing the most to this research, and briefly exploring the current developments and research gaps in the field of microalgae bio-granulation. However, it lacked Collaboration	(Syahirah et al. 2023)

	inorganic nutrients on microalgae granulation and the use of Chlorella Vulgaris species are largely unexplored.					analysis, Journal and subject area analysis, Temporal analysis, geographic distribution of publications and collaborations of institutions, and research hotspot areas in the field (emerging and present).	
A bibliometric analysis of industrial wastewater treatments from 1998 to 2019	The analysis retrieved 9413 publications, with a focus on applying and optimizing existing technologies. China leads in research output, while the United States and European countries produce high-quality papers. The top techniques identified are adsorption, oxidation, and the activated sludge process. The study also highlights the shift towards	1998 to 2019	Web of Science Core Collection	("wastewater treat∗" or "water pollution control" or "polluted water control" or "sewage treat∗" or "effluent treat∗") AND ("industrial" or "industry")	Bibexcel software and Loglet Lab 4	The research primarily focused on structured information such as keywords and international classification numbers. The analysis did not extensively consider unstructured information or explore areas where there is limited existing research (blank technologies). To address this limitation, future researchers are encouraged to incorporate artificial intelligence techniques, such as citation networks or information maps, to further explore	(Mao et al. 2021)vv

	addressing specific wastewater types. The S-curve analysis indicates potential in physical and chemical treatment technologies, while biological treatment approaches saturation.					the development path of technologies and identify promising areas within the field of industrial wastewater treatment.	
State of the art on granular sludge by using bibliometric analysis	The study analyzed 2,460 articles were published in 276 journals across 44 subject categories and were affiliated with 1,420 institutes from 68 countries. Various emerging techniques and granular reactors, along with precise bio-analytical technology, were identified as key tools	1992 to 2016	Science Citation Index EXPANDED (SCI-EXPANDED)	(“granul* sludge*” OR “sludge* granul*” OR “sludge pellet*” OR “pellet* sludge”)	Bibexcel software	The bibliometric technique has limitations in providing detailed analysis of granular sludge formation and mechanisms, necessitating additional methods for in-depth exploration. The role of EPS in granulation and the authentic granulation mechanism require further investigation using bio-analytical breakthroughs.	(Zheng et al. 2018)

	for investigating the mechanisms between microorganisms and EPS (extracellular polymeric substances) and achieving desired removal requirements (such as nitrogen removal, phosphorus removal, sulfate reduction, dechlorination, decolorization, or full nutrient removal) and bio-energy production (such as methane, biogas, and biohydrogen) pathways.						

Table 2: Top 10 most contributing countries in the field of biogranulation for wastewater treatment from 1992 to 2022.

Country	Publication	Citation	H-index	Highest cited article	Reference	Journal	Citation of highest cited article
China	782	21310	73	Performance of high-loaded ANAMMOX UASB reactors containing granular sludge	Tang et al., (2011)	*Water Research*	522
United States	142	5608	46	Occurrence and removal of pharmaceuticals and personal care products (PPCPs) in an advanced wastewater reclamation plant	Yang et al., (2011)	*Water Research*	439
Netherlands	131	9833	56	Startup of reactors for anoxic ammonium oxidation: Experiences from the first full-scale anammox reactor in Rotterdam	van der Star et al., (2007)	*Water Research*	1048
Japan	109	4449	34	Startup of reactors for anoxic ammonium oxidation: Experiences from the first full-scale anammox reactor in Rotterdam	van der Star et al., (2007)	*Water Research*	1048
Spain	85	3822	37	Aggregate size and architecture determine microbial activity balance for one-stage partial nitritation and anammox	Vlaeminck et al., (2010)	*Applied and Environmental Microbiology*	308

Taiwan	65	2024	27	Biosorption of long-chain fatty acids in UASB treatment process	Hwu et al., (1998)	*Water Research*	153
Italy	63	1613	25	The effect of nitrite inhibition on the anammox process	Jin et al., (2013)	*Water Research*	278
Canada	58	2132	28	Biosorption of lead(II), cadmium(II), copper(II) and nickel(II) by anaerobic granular biomass	Hawari and Mulligan, (2006)	*Bioresource Technology*	259
Singapore	57	2249	30	Biodegradation of p-nitrophenol by aerobic granules in a sequencing batch reactor	Yi et al., (2006)	*Environmental Science and Technology*	200
Australia	53	2313	27	Simultaneous nitrification, denitrification, and phosphorus removal from nutrient-rich industrial wastewater using granular sludge	Yilmaz et al., (2008)	*Biotechnology and Bioengineering*	222

1300 **Table 3:** The top 10 most prolific authors in the field of biogranulation for wastewater treatment from 1992 to 2022.

Author	**Publication**	**Citation**	**H-index**	**Institution**	**Scopus ID**	**ORCID**	**Highest cited article**	**Reference**	**Journal**	**Citation of highest cited article**
Jin Rencun	40	1624	25	Hangzhou Normal University, Hangzhou, China	1.01E+10	Nil	The effect of sulfide inhibition on the ANAMMOX process	Jin et al., (2013)	*Water Research*	210
Lee Duu-Jong	39	1472	23	City University of Hong Kong, Kowloon, Hong Kong	5.81E+10	0000-0002-8820-8097	Microbial communities of aerobic granules: Granulation mechanisms	Lv et al., (2014)	*Bioresource Technology*	146
van Loosdrecht Mark C.M.	39	4080	28	Delft University of Technology, Delft, Netherlands	7E+09	0000-0003-0658-4775	Biodegradation of p-nitrophenol by aerobic granules in a sequencing batch reactor	Yi et al., (2006)	*Environmental Science and Technology*	200

Tay Joohwa	37	2172	21	University of Calgary, Calgary, Canada	7.1E+09	Nil	Degradation of phenol in wastewater in an upflow anaerobic sludge blanket reactor	Ke et al., (2004)	*Water Research*	149
Yu-You Li	36	1033	20	Tohoku University, Sendai, Japan	7.5E+09	0000-0002-3659-5005	High-throughput profiling of microbial community structures in an ANAMMOX-UASB reactor treating high-strength wastewater	Cao et al., (2016)	*Applied Microbiology and Biotechnology*	166
Peng Yongzhen	33	1198	20	Beijing University of Technology, Beijing, China	7.4E+09	0000-0002-4702-3774	Treatment of anaerobic sludge digester effluents by the CANON	Vázquez-Padín et al., (2009)	*Journal of Hazardous Materials*	149

							process in an air pulsing SBR			
Mosquera-Corral Anuska	29	1183	20	Universidad de Santiago de Compostela, Santiago de Compostela, Spain	6.6E+09	0000-0003-1925-680X	Treatment of anaerobic sludge digester effluents by the CANON process in an air pulsing SBR	Vázquez-Padín et al., (2009)	*Journal of Hazardous Materials*	149
Campos Jose Luis	28	1177	20	Universidad de Santiago de Compostela, Santiago de Compostela, Spain	5.61E+10	0000-0001-5750-1699	Treatment of anaerobic sludge digester effluents by the CANON process in an air pulsing SBR	Vázquez-Padín et al., (2009)	*Journal of Hazardous Materials*	149
Zheng Ping	26	1676	20	Zhejiang University, Hangzhou, China	3.52E+10	Nil	Performance of high-loaded ANAMMOX UASB reactors	Tang et al., (2011)	*Water Research*	522

							containing granular sludge			
Yu Hangqing	25	1618	19	Chinese Academy of Sciences, Beijing, China	3.52E+10	Nil	Granulation of activated sludge in a pilot-scale sequencing batch reactor for the treatment of low-strength municipal wastewater	Ni et al., (2009)	*Water Research*	270

1311 **Table 4:** The top 10 most contributing institutions in the field of biogranulation for wastewater treatment from 1992 to 2022.

Institution	Publication	Citation	H-index	Location	Affiliation ID	Highest cited article	Reference	Journal	Citation of highest cited article
Harbin Institute of Technology	104	2798	32	Heilongjiang, China	60019616	High-throughput profiling of microbial community structures in an ANAMMOX-UASB reactor treating high-strength wastewater	Cao et al., (2016)	*Applied Microbiology and Biotechnology*	166
Ministry of Education China	84	1798	27	Beijing, China	60001604	Treatment of synthetic wastewater by a novel MBR with granular sludge developed for controlling membrane fouling	Li et al., (2005)	*Separation and Purification Technology*	117
Delft University of Technology	82	7164	45	Zuid-Holland, Netherlands	60006288	Startup of reactors for anoxic ammonium oxidation: Experiences from the first full-	van der Star et al., (2007)	*Water Research*	1049

						scale anammox reactor in Rotterdam			
Beijing University of Technology	81	1853	28	Beijing, China	60022281	High-throughput profiling of microbial community structures in an ANAMMOX-UASB reactor treating high-strength wastewater	Cao et al., (2016)	*Applied Microbiology and Biotechnology*	166
Tongji University	53	1637	23	Shanghai, China	60073652	Characterization of stratified EPS and their role in the initial adhesion of anammox consortia	Wang et al., (2020)	*Water Research*	150
Nanyang Technological University	52	2138	29	Singapore City, Singapore	60005510	Biodegradation of p-nitrophenol by aerobic granules in a sequencing batch reactor	Yi et al., (2006)	*Environmental Science and Technology*	201
Chinese Academy of Sciences	47	1364	22	Beijing, China	60019499	Perfluoroalkyl substances (PFASs) in wastewater treatment plants and drinking water treatment plants:	Pan et al., (2016)	*Water Research*	130

						Removal efficiency and exposure risk			
Zhejiang University	43	2095	25	Zhejiang, China	60003970	Performance of high-loaded ANAMMOX UASB reactors containing granular sludge	Tang et al., (2011)	*Water Research*	523
Hangzhou Normal University	41	1634	25	Zhejiang, China	60069717	The effect of sulfide inhibition on the ANAMMOX process	Jin et al., (2013)	*Water Research*	210
University of Science and Technology of China	40	2138	29	Anhui, China	60019118	Granulation of activated sludge in a pilot-scale sequencing batch reactor for the treatment of low-strength municipal wastewater	Ni et al., (2009)	*Water Research*	271

Table 5: Top 10 most productive journals in this field and their most cited articles on biogranulation for wastewater treatment from 1992 to 2022.

Journal	Publication	Citation	H-index	Highest cited article	Reference	Citation of highest cited article
Bioresource Technology	249	9851	60	Performance of membrane-less microbial fuel cell treating wastewater and effect of electrode distance and area on electricity production	Ghangrekar and Shinde, (2007)	281
Water Research	192	14277	72	Startup of reactors for anoxic ammonium oxidation: Experiences from the first full-scale anammox reactor in Rotterdam	van der Star et al., (2007)	1049
Water Science and Technology	102	2466	26	Selection of slow growing organisms as a means for improving aerobic granular sludge stability	de Kreuk and van Loosdrecht, (2004)	341
Science of the Total Environment	78	1346	23	Application of bacteria involved in the biological sulfur cycle for paper mill effluent purification	Janssen et al., (2009)	120
Chemosphere	75	1699	28	Nitrogen removal performance and microbial community analysis of an anaerobic up-flow granular bed anammox reactor	Cho et al., (2010)	160

Chemical Engineering Journal	56	2102	27	Simultaneous nitrification, denitrification and phosphorus removal in an aerobic granular sequencing batch reactor with mixed carbon sources: reactor performance, extracellular polymeric substances and microbial successions	Wang et al., (2018)	205
Journal of Hazardous Materials	49	2033	28	Biosorption of Acid Yellow 17 from aqueous solution by non-living aerobic granular sludge	Gao et al., (2010)	149
Environmental Technology United Kingdom	46	911	16	Characteristics of aerobic granules grown on glucose and acetate in sequential aerobic sludge blanket reactors	Tay et al., (2002)	151
Applied Microbiology and Biotechnology	45	1808	27	Treatment of dairy effluents in an aerobic granular sludge sequencing batch reactor	Schwarzenbeck et al., (2005)	204
Biochemical Engineering Journal	37	907	22	Distribution of extracellular polymeric substances in anammox granules and their important roles during anammox granulation	Ni et al., (2015)	93

Table 6: Performance matric in the Scopus database of the top 10 most productive journals in this field of biogranulation for wastewater treatment from 1992 to 2022.

Journal	Publisher	Subject area	ISSN	Scopus coverage years	CiteScore (2021)	SJR (2021)	SNIP (2021)	Quartile
Bioresource Technology	Elsevier	Environmental Engineering, Waste Management and Disposal, Bioengineering, Renewable Energy, Sustainability and the Environment	0960-8524	from 1991 to Present	17.4	2.354	2.06	Q1
Water Research	Elsevier	Civil and Structural Engineering, Environmental Engineering, and Water Science and Technology	0043-1354	from 1967 to Present	18	2.806	2.499	Q1
Water Science and Technology	IWA Publishing	Water Science and Technology, and Environmental Engineering	0273-1223	from 1980 to Present	3.4	0.447	0.648	Q2
Science of the Total Environment	Elsevier	Environmental Engineering, Pollution, Environmental Chemistry, and Waste Management and Disposal	0048-9697	from 1972 to Present	14.1	1.806	2.175	Q1

Chemosphere	Elsevier	Environmental Engineering, Pollution, Public Health, Environmental and Occupational Health, Toxicology and Mutagenesis	0045-6535	from 1972 to Present	11.7	1.505	1.603	Q1
Chemical Engineering Journal	Elsevier	General Engineering	0300-9467	from 1970 to 1993	Nil	Nil	Nil	Q1
Journal of Hazardous Materials	Elsevier	Environmental Engineering, Pollution, Health, Toxicology and Mutagenesis, and Waste Management and Disposal	0304-3894	from 1979 to Present	14.7	1.991	2.062	Q1
Environmental Technology United Kingdom	Taylor & Francis	Environmental Chemistry, Water Science and Technology, and Waste Management and Disposal	0959-3330	from 1990 to Present	5.4	0.523	0.79	Q2
Applied Microbiology and Biotechnology	Springer Nature	Genetics and Molecular Biology: Biotechnology, and Applied Microbiology and Biotechnology	0175-7598	from 1984 to Present	8.8	0.987	0.327	Q1

Biochemical Engineering Journal	Elsevier	Environmental Engineering, Biomedical Engineering, Bioengineering, and Genetics and Molecular Biology: Biotechnology	1369-703X	from 1998 to Present	6.7	0.743	0.998	Q1

Table 7: Different wastewater treated using biogranulation technology and various parameters examined

Type of wastewater	Objectives	Added components to the wastewater	Volume of wastewater used in reactor	Parameters examined	Reference
Synthetic wastewater	To investigate the granular properties, pollutant removal capabilities, and microbial communities of microalgal-bacterial granular sludge	chemical oxygen demand (400 mg/L), ammonium nitrogen (50 mg/L), phosphate phosphorus (10 mg/L), magnesium sulfate heptahydrate (52 mg/L), ferrous sulfate heptahydrate (25 mg/L), calcium chloride	1.0 L	The amount of protein and polysaccharide, size of granule and chlorophyll content	Xiao et al., (2022)

	throughout the transition process.	(40 mg/L), and trace element solution (1 mL/L)			
Real Municipal wastewater in Saskatchewan, Canada	To examine the efficiency of granule-based large-scale wastewater treatment plants (LWWTPs).	Nil	Nil	Total Nitrogen, Kjeldhal nitrogen, ammonium nitrogen, phosphorus, coliform and E. coli	Pishgar et al., (2020)
Synthetic wastewater	The study aims to contrast the biogranulation process in two granular sequencing batch reactors operating at different organic loading rates, despite both rates being below the recommended optimum or minimum values for the anaerobic granular sludge) technology.	In reactor R1, glucose (0.812 g), while in reactor R2, the glucose (0.369 g). Additionally, both reactors contained ammonium chloride (0.15 g) and potassium dihydrogen phosphate (0.043 g)	1.8 L	Organic loading rate, the morphology of sludge flocs and aerobic granules, sludge settling velocity and mixed liquor volatile suspended solids	Czarnota and Masłoń, (2019)

Synthetic wastewater	To comprehend the impact of nitrate on the formation of anaerobic granular sludge granules and analyze the underlying mechanisms using quantitative detection, microbial community analysis, and metabolomics biotechnology	Ammonium chloride at 0.382 g/L, sodium acetate at 0.769 g/L, glucose at 1.125 g/L, disodium hydrogen phosphate at 0.088 g/L, monosodium dihydrogen phosphate at 0.024 g/L, calcium chloride at 0.056 g/L, and magnesium chloride at 0.079 g/L	1.7 L	Settling velocity, ammonium, total nitrogen and chemical oxygen demand	Wu et al., (2023)
Synthetic wastewater	To examine the impact of algae growth on the formation of aerobic bacteria granular sludge and the underlying mechanism by which algae influences biogranular formation	glucose at 260 mg/L, sodium acetate at 156.9 mg/L, ammonium chloride at 192 mg/L, sodium bicarbonate at 200 mg/L, potassium dihydrogen phosphate at 12 mg/L, potassium phosphate trihydrate at 19 mg/L, magnesium sulfate heptahydrate at 11 mg/L, ferrous sulfate heptahydrate at 16.35 mg/L, calcium chloride at 10 mg/L, and trace elements at a concentration of 1 mL/L.	2.54 L	characteristics of aerobic bacteria granular sludge including its physicochemical properties, nutrient removal capabilities, extracellular polymeric	Liu et al., (2023)

				substances, and microbial community	
Real wastewater taken from aeration tank of the WWTP in Poland	To investigate the impact of algae growth on the formation of aerobic bacteria granular sludge and the mechanisms through which algae affects the granular formation.	Nil	2,080,000 L	Chemical oxygen demand, total nitrogen, ammonium nitrogen, total phosphorus, nitrogen content, mixed liquor volatile suspended solids, mixed liquor suspended solids, sludge volumetric index, dissolved oxygen, and size of granules	Świątczak and Cydzik-Kwiatkowska, (2018)

Synthetic textile wastewater	To demonstrate that magnetic powder activated carbon can enhance and expedite the biogranulation process by serving as a supportive substrate for microbial growth	Ethanol (0.125 g/L), glucose (0.75 g/L), sodium acetate (0.75 g/L), ethylenediaminetetraacetic acid (0.02 g/L), dipotassium phosphate (0.58 g/L), ammonium chloride (0.16 g/L), monopotassium phosphate (0.23 g/L), magnesium sulphate heptahydrate (0.09 g/L), calcium chloride dihydrate (0.07 g/L), 50 mg/L of nixed azo dyes and trace solution (1 ml/L).	3 L	Biomass concentration, colour removal, suspended solids concentration, microstructural, physical and chemical characterization of biogranules	Omar et al., (2023)
Real municipal wastewater	To evaluate the effectiveness of a combined physico-chemical and biological technology of granular activated carbon sequencing batch reactor for wastewater treatment	Nil	4 L	Mixed liquor suspended solids, mixed liquor volatile suspended solids, turbidity, chemical oxygen demand, ammonia, nitrate, and phosphate removal	Verma et al., (2023)