Global trends and research hotspots of aerobic granular sludge for wastewater treatment using Scopus database: A bibliometric analysis

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Graphical abstract
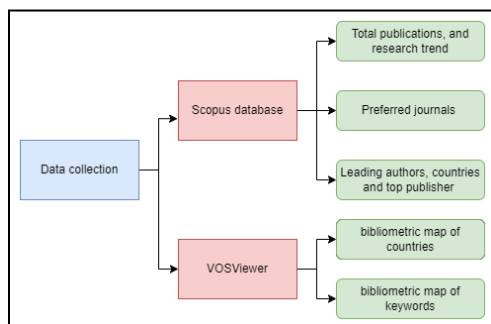
Abstract

The aerobic granular sludge (AGS) system is a promising technology that is suitable for the treatment of various types of wastewaters. This system has received great attention from many researchers due to its wide range of applications and potential as a cost effective system. However, only a few reports are available in analyzing the progress of AGS research in wastewater treatment over the last 20 years. Therefore, in the present work, a bibliometric analysis was carried out to trace the global research trends and current hotspots of AGS in wastewater treatment from 1997 to 2020, based on the Scopus database. The bibliometric data was visualized using the VOSviewer software. A total of 1,347 articles were published in 160 journals across 19 subject categories, involving 50 countries and 129 academic institutions. Results showed that Bioresource Technology (175, 12%), Water Research (94, 6.96%), and Huanjin Kexue Environmental Science (78, 5.77%) dominated in the top 3 journals. Environmental Science (1036, 38%), China (716, 53%), and Harbin Institute of Technology (98, 7.28%) were the most productive subject category, country, and academic institution, respectively. The AGS research hot topics and future research directions were discovered through the analysis of the most frequently used keywords obtained in bibliometric maps.

Keywords: Aerobic granular sludge, Bibliometric analysis, Global research trend, Scopus, VOSviewer,

1.0 INTRODUCTION

The aerobic granular sludge (AGS) system is regarded as one of the effective technologies in treating a wide range of wastewaters, which has several advantages over conventional activated sludge (AS) systems in terms of performance and cost efficiency. This system can be operated at high organic loadings, short retention time, low energy consumption, and low operational cost [1,2]. Moreover, the system does not require a large treatment area, able to reduce the operating cost up to 25%, and decrease the energy requirement for wastewater treatment by 30% [3]. AGS was successfully developed in a sequencing batch reactor (SBR) in 1997 [4] and is well known for its excellent performance in eliminating nutrient content and pollutants from low and high strength wastewaters, in a single reactor [5,6,7,8]

Studies on AGS has been published in a wide range of journals contributed by authors from across the world. However, little effort has been made to accumulate bibliographic data on global outputs of AGS research field in wastewater treatment. Bibliometric analysis is a method used to identify the current and past research trends in a specific

area of knowledge. It is a statistical approach to determine the number of articles published over the year and evaluates the impact and relevance of authors, countries, and institutions that have contributed to the research field [9]. This approach also involves an in-depth analysis of the underlying collaborative network between countries/academic institutions, as well as the relationship of author keywords in respect to the field of study. Bibliometric analysis is useful to the researchers especially junior researchers as it helps them to explore and broaden their networking with other countries or institutions. Bibliometric guides scholars in publishing research papers in high quality journals, by providing tools like h-index, CiteScore, and total number of citations, which are used to assess the impact of journals

Therefore, this work aims to reveal the distribution patterns of research articles and evaluates the contribution of authors, countries, academic institutions, and collaboration patterns in the AGS research field. This article further highlights the common terminology, research topics and provides a potential guide for future research related to AGS for wastewater treatment. In this study, the Scopus web was selected to analyse the research trends of AGS from year 1997 to 2020, as it is the world's largest abstract and citation database of peer-reviewed literature, covering a wide range of topics and subjects compared to other databases [10]. The VOSviewer software was used to generate bibliometric maps based on bibliographic data retrieved from Scopus, which comprises co-authorship and co-occurrence analysis, including countries and author keywords. A co-occurrence analysis was conducted to assess the content of published research work. This analysis is important to identify the ongoing research activities of AGS since year 1997 to 2020.

2.0 METHODOLOGY AND SEARCH STRATEGY

Bibliometric data were obtained from the Scopus database, on the 8th of August, 2021. The search strategy was done by words from the title, abstract and keywords. The terms: ("aerobic granul*") or ("aerobic granul* sludge*") or ("aerobic sludge* granul*") or ("AGS") and ("wastewater* treatment*") or ("waste-water" or "waste water" or "wastewater*") or ("biological* treatment*") or ("sequen* batch reactor*") or ("SBR") were used as search themes in the Scopus database to extract publications from 1997 to 2020. Year 1997 is the oldest publication in aerobic granulation technology as Morgenroth et al. (1997) was the first author that observed the formation of aerobic granular sludge developed in a sequencing batch reactor (SBR). This is followed by limiting the search to (a) document type: Article, and (b) source type: Journal.

The The query string in the advanced search was as follows: TITLE-ABS-KEY ("aerobic granul*") OR TITLE-ABS-KEY ("aerobic granul* sludge*") OR TITLE-ABS-KEY ("aerobic sludge* granul*") OR TITLE-ABS-KEY ("AGS") AND TITLE-ABS-KEY ("wastewater* treatment*") OR TITLE-ABS-KEY ("waste-water" OR "waste water" OR "wastewater*") OR TITLE-ABS-KEY ("biological* treatment*") OR TITLE-ABS-KEY ("sequen* batch reactor*") OR TITLE-ABS-KEY ("SBR") AND (EXCLUDE (PUBYEAR , 2022) OR EXCLUDE (PUBYEAR , 2021)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SRCTYPE , "j")). The query string resulted in 1,367 documents. Since this bibliometric study focused on bibliographic data from research

articles, thus, it is important to eliminate any review articles that might be included in the publications. A total of 49 potential review articles were identified by adding phrases in the query string, where the title or abstract of these potential review articles contained phrases such as review, overview, critical, revisit, advance, highlight, trends, bibliometric and scientometric. Out of 49 documents, 20 documents were identified as review articles after screening the titles and abstracts of each article. These articles were then selected to obtain the Scopus EID, a unique academic work identifier, by exporting the file in the Scopus database into Microsoft Excel. The 16 review articles were removed by adding the EID number to the query string. Therefore, only 1,347 documents were retrieved for further analysis. In addition, Boolean's operators (OR, AND) and Boolean's modifiers (quotation marks, asterisk, and bracket) were used in the query string to connect the search terms involved, capture the likely occurrences of the considered terms, and help to clearly identify the scope of the intended topic.

2.1 Data Analysis

Data collected from the Scopus database were exported to Microsoft Excel (CSV files) for further assessment. The main information that comprised the journals, authors, institutions, countries, subject categories and outputs were analysed in this bibliometric study. Meanwhile, total publications, total citations, CiteScore, and h-index were selected to determine the productivity of the journals, authors, academic institutions, and countries. Two types of research collaborations were analyzed among the leading countries, including "single country publications" and "international collaborative publications". These collaborations were categorized by the affiliation of the authors. Single country publications involve authors from the same country in the publication, whereas international collaborative publications involve researchers from multiple countries. Similar concepts were applied for academic institutions, where the term single institute publication was assigned to articles that were co-authored by researchers from the same institute. The term inter-institutionally collaborative publication was used to label articles if the authors were affiliated to multiple institutions on a single publication

2.2 Bibliometric Maps, Co-Authorship And Co-Occurrences

Bibliometric map is a map of knowledge that helps the researchers to identify the trends and hotspot of the aerobic granular sludge studies, by visualizing the data from Scopus between 1997 to 2020. The bibliometric maps were generated using the VOSviewer software. The main information such as bibliographic and keywords were extracted from 1,347 articles and exported to the VOSviewer software. Co-authorship and co-occurrence were analyzed based on the bibliometric maps visualized by the software. Map of the authors, organizations, and countries can be created for co-authorship analysis. Meanwhile, analysis of co-occurrence can be conducted by creating author keywords map or index keywords map in the VOSviewer software. In this study, the bibliometric maps of countries and author keywords were created for co-authorship and co-occurrences analysis. Both countries and author keywords are known as items which refer to the object of interest [10]. The closer the distance of each item, the stronger

the relationship between them. In the case of co-authorship analysis, the distance between the countries visualized on the map indicates the strength of research collaboration among the countries [11]. In addition, the items are connected with a link, where the frequency of joint research work between items are identified based on the link strength. For example, the higher the value of the link strength, the stronger the research collaboration between the two countries. The link strength is addressed as the number of publications that the two countries have collaborated [10]. Total link strength indicates the total number of publications of a given country affiliated to other countries. This is similar to the co-occurrence analysis, where the number of publications are determined based on the value of link strength that links the two author keywords in bibliometric maps. In this case, link strength connects two author keywords that have been used in the publication. For example, if both author keywords have only one link strength, it shows that only one publication can be found using the two keywords.

The analysis of co-authorship involved 1,347 articles published by 2,000 authors including first author and co-authors, and affiliated to 50 countries around the world. All countries were re-clustered based on four continents: Asia, Europe, America, and Africa. The co-occurrence analysis involved 250 author keywords from 1,347 articles. The minimum number of occurrences of a keyword was set to three. Prior to generating the co-occurrence map in VOSviewer, the data of author keywords were analysed to avoid redundancy of similar keywords. A total of 100 synonym keywords were identified and merged, resulting in the reduction of keywords from 350 to the 250 final keywords. For

example, sequencing batch reactor, sequencing batch reactor (SBR), sequential batch reactor, and SBR were re-labelled as SBR. In VOSviewer, the overlay visualization mode was selected to exhibit the average publication year of each keyword.

3.0 RESULT AND DISCUSSIONS

3.1 Publication Outputs

For a period of 24 years, a total of 1,347 research articles had been published. The results showed that the articles used in the AGS research field were published in eight different languages. A majority of the articles (86%) were published in English, followed by Chinese (13%). The other languages (1%) included Polish, Portuguese, French, Malay, Spanish, and German and were published in less than four articles. This revealed that English was the primary medium of communication among researchers from various countries. Figure 1 shows the growth of research articles from year 1997 to 2020. The first AGS publication was recorded in 1997 and it was observed that there was no increase in the number of publications up to year 2001, where the cumulative publications were less than 10. Nonetheless, there was a significant increase in the number of annual publications (15 publications) recorded in year 2002, indicating the beginning of great interest in the field of AGS research. The number of annual publications steadily increased from year 2002 to 2020. By 2020, a total of 162 publications were recorded and it is expected that the annual publications will continue to grow every year.
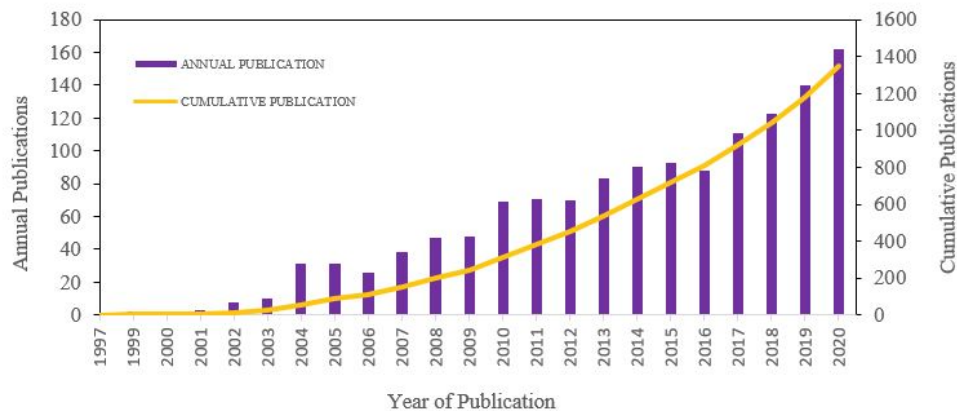

Figure 1. The annual and cumulative research articles of AGS in wastewater treatment from 1997 to 2020).

3.2 Preferred Journals and Subject Category

Table 1 displays the top 10 most productive journals contributing to the growth of research activity on aerobic granules technology in wastewater treatment worldwide. This table comprises the performance of top 10 journals with subject category, CiteScore, total citation as well as the most cited articles. Based on the Scopus database, it was summarized that six publishers had the most publications in

aerobic granulation studies. Of the top 10 journals, 5 journals were published under Elsevier, as listed in Table 1. The top 2 publishers were conquered by Elsevier, while the rest of the publishers including Science Press, IWA Publications, Springer Nature, Desalination Publications, and Taylor & Francis were in the top 3, top 4, top 5, top 6, and top 8, respectively.

Amongst the top 10 journals shown in Table 1, Bioresource Technology published the largest number of articles with 175 publications, making it the most productive journal and

dominated 12% of total publications. This is followed by Water Research (94, 6.96%), Huanjing Kexue Environmental Science (78, 5.77%), and Water Science and Technology (59, 4.37%). Chemical Engineering Journal was the least productive journal, it ranked tenth with only 34 articles. However, interestingly, the total citations of this journal was higher than Huanjing Kexue Environmental Science, which ranked third as displayed in Table 1. The total citations of Huanjing Kexue Environmental Science was only 230, significantly lower compared to Chemical Engineering Journal, which received total citations of 1,096. Also, Chemical Engineering Journal had the highest CiteScore (17.2) and ranked top in the category of Engineering (Q1, 3/336). Water Research received the highest number of citations with a total of 6,171, followed by Bioresource Technology (4,821), Applied Microbiology and Biotechnology (2,276), and Water Science and Technology (1,460). In addition, Water Research achieved the highest cited articles with 629 citations between year 1997 to 2019.

Despite the total publications, highlighting the ranking of CiteScore and h-index could help the researchers to determine the preferred journals with the highest quality in aerobic granulation fields. Six journals had a CiteScore of 7 and above. Chemical Engineering Journal (17.2), Water Research (15.6), and Bioresource Technology (14.8) were the top 3 journals with the highest CiteScore. Meanwhile, Bioresource Technology, Water Research and Applied Microbiology and Biotechnology ranked the top 3 highest h-index of 49, 46 and 30, respectively, for overall productivity. This indicates that the aerobic granulation field is increasingly drawing the interest of researchers, as the studies have been successfully published and their importance recognized in high impact journals. The lowest CiteScore belongs to Desalination and Water Treatment (1.6). Although it ranked sixth with 40 articles, the CiteScore and total citations of this journal were relatively lower compared to other journals. This was probably because most of the articles published in Desalination and Water Treatment were not easily accessible to the readers which then resulted in low citations and affected the Journal CiteScore. This is evidenced when the journal obtained the lowest total citations

of only 131 and the most cited articles in the journal achieved only 17 citations. In addition, Desalination and Water Treatment also owned the lowest ranking of h-index (8), similar to Huanjing Kexue Environmental Science. Although Huanjing Kexue Environmental Science ranked third in the top 10 journals, it still earned the lowest h-index. This was likely due to the main language of the publication, which is in Chinese, making it less accessible to the English readers. Publishing in journals with a higher CiteScore and h-index may help to advance the career path of researchers, by broadening the communication network and influence in their research field. However, besides CiteScore, choosing the right journal is also important so that it is able to contribute to the progress of the field, ensure that the research goals are well-delivered to the right audience as well as able to increase the knowledge of the significant work published in the journal [9,12].

Aerobic granulations are increasingly drawing interest of researchers worldwide. This is justified as the studies have crossed 10 subject areas in the Scopus database. The top 5 subject areas that showed the highest total publications on Scopus belonged to Environmental Science (1,036 articles), Chemical Engineering (441 articles), Biochemistry, Genetics and Molecular Biology (243 articles), Engineering (225 articles), and Energy (216 articles). There was a total of 2,714 articles in the subject category. This can be attributed to the data shown in Table 1, where among the 10 most productive journals, six journals were in the category of environmental science. The journals include Bioresource Technology, Water Research, Huanjing Kexue Environmental Science, Water Science and Technology, Journal of Hazardous Materials, and Environmental Technology United Kingdom. The aerobic granulation field is extensively recognized in environmental science categories. As environmental issues become increasingly concerning, it is believed that aerobic granulation could attract many researchers to continue exploring this field by using aerobic granular sludge to solve various environmental issues.

Table 1. The top 10 most productive journals of AGS research area in wastewater treatment.

No	Journal	TP (%)	Total Citations	Cite Score 2020	H-index	Category/ Subcategory	Rank	Quartile	Publisher
1	Bioresource Technology	174 (12.92)	4815	14.8	49	Environmental Science/ Environmental Engineering	2/146	Q1	Elsevier
2	Water Research	94 (6.96)	6171	15.6	46	Environmental Science/ Water Science and Technology	1/225	Q1	Elsevier
3	Huanjing Kexue Environmental Science	78 (5.77)	230	2.4	8	Environmental Science/ General Environmental Science	97/220	Q2	Science Press
4	Water Science and Technology	59 (4.37)	1460	3.3	18	Environmental Science/ Water Science and Technology	87/225	Q2	IWA Publishing
5	Applied Microbiology Biotechnology	58 (4.29)	2276	7.0	30	Immunology and Microbiology/ Applied Microbiology and Biotechnology	20/113	Q1	Springer Nature

6	Desalination and Water Treatment	40 (2.96)	131	1.6	8	Engineering/ Ocean Engineering	54/96	Q3	Desalination Publications
7	Journal of Hazardous Materials	40 (2.96)	767	13.4	25	Environmental Science/ Environmental Engineering	4/146	Q1	Elsevier
8	Chemosphere	36 (2.66)	1024	10.1	19	Medicine/ Public Health, Environmental and Occupational Health	15/526	Q1	Elsevier
9	Environ-mental Technology United Kingdom	35 (2.59)	484	4.2	12	Environmental Science/ Water Science and Technology	60/225	Q2	Taylor & Francis
10	Chemical Engineering Journal	34 (2.52)	1096	17.2	23	Engineering/ Industrial and Manufacturing Engineering	3/336	Q1	Elsevier

3.3 Leading Authors

About two thousand authors had contributed to the aerobic granulation studies in wastewater treatment with at least one publication. Table 2 lists the top 14 most prolific authors in aerobic granular sludge research, affiliated to eight countries. It was evaluated based on the authors' contribution in terms of total publications, total citations and h-index, from their first publication between 2001 to 2014. Five authors out of the 14 most prolific authors were from China, followed by Spain (3 authors), Singapore (2 authors), Canada (1 author), Taiwan (1 author), the Netherlands (1 author), and Poland (1 author). Table 2 records the role of authors in their first publication, where two authors had a role as the first author, seven as a co-author, three as a corresponding author, and the remaining two authors had both roles as first author and corresponding author, respectively. The affiliation of the authors indicated that aerobic granulation was within the research fields related to environmental, science and engineering

J.H. Tay (101, 7.50%) from the University of Calgary, Canada, D.J. Lee (61, 4.53%) from National Taiwan University, Taiwan, and M.C.M. Van Loosdrecht (46, 3.41%) from Delft University of Technology, the Netherlands were the top 3 most prolific authors. J.H. Tay ranked first with the highest total citations of 5,406, 48 h-index and 101 total publications since 2001, which revealed his undoubted influence and expertise in aerobic granulation research. Three authors from the University of Science and Technology of China, Wuhan University and Zhejiang University of Technology, China ranked fourth (H.Q. Yu), 10th (H. Wang) and 13th (J. Li), respectively. Another two authors from China, C. Wan (ranked ninth) and X. Liu (ranked 11th) are both affiliated to Fudan University. We also found that, the year of the first publication dates back to 2001, which as shown in Table 2 refers to the same article [13] written by two prolific authors, Y. Liu (ranked 5th) and J.H. Tay (ranked 1st). Although both authors were originally from Nanyang Technological University, Singapore, the author J.H. Tay is currently shown to be affiliated with the University of Calgary, Canada. Another prolific author from Nanyang Technological University, Singapore, is S.T.L. Tay (ranked 12th) with a total of

21 publications and total citations of 1,858, since 2002. The sixth and 14th top authors, A. Mosquera-Corral and R. Mendez, are both affiliated with the University of Santiago de Compostela, Spain. These two prolific authors also had the same roles as co-author in the same article [14] published in 2004, as displayed in Table 2. The rest of the prolific authors are J.L. Campos-Gomez (ranked seventh), A. Cydzik-Kwiatkowska (ranked eighth), and J. Li (ranked 13th), respectively, from Adolfo Ibáñez University, Spain, the University of Warmia and Mazury, Poland, and Zhejiang University of Technology, China.

Out of 1347 articles, 5 articles received more than 450 citations between year 1997 and 2021. The most cited article in aerobic granulation field was "aerobic granulation in a sequencing batch reactor" with 654 citations, which was published in Water Research in 1999. The second most frequently cited article was "Composition and distribution of extracellular polymeric substances in aerobic flocs and granular sludge", published in Applied and Environmental Microbiology with 601 citations. This was followed by the earliest publication in aerobranulation studies (year 1997), entitled "Aerobic granular sludge in a sequencing batch reactor", which received 501 citations. The article "Simultaneous COD, nitrogen, and phosphate removal by aerobic granular sludge" published in Biotechnology and Bioengineering, had 474 citations. The article, "Full scale performance of the aerobic granular sludge process for sewage treatment", published in 2015 in Water Research, received 450 citations. Interestingly, M.C.M. Van Loosdrecht, the most prolific authors, with 32 h-index was the co-author for the Top 1, Top 3, Top 4 and Top 5 most cited articles. This demonstrates M.C.M. Van Loosdrecht's dominance and expertise in aerobic granulation field This was followed by J.J. Heijnen and P.A. Wilderer, who also contributed the most as co-authors in the Top 5 most cited articles, with h-indexes of 5 and 8, and total citations of 1980 and 2264, respectively. Besides, out of 5 most cited articles, 3 articles were published in Water Research, the Top 2 most productive journals as displayed in Table 1.

Table 2. List of the 14 most prolific authors in AGS research area based on total number of publications.

Rank	Author	Year of 1st Publication	Total Publication (%)	h-index	Total Citation	Current affiliation	Country	Most Cited Articles	Citations
1	Tay, Joohwa	2001[a]	101(7.50)	48	5406	Department of Civil Engineering, University of Calgary	Canada	High organic loading influences the physical characteristics of aerobic sludge granules	366
2	Lee, Duu-Jong	2007[c]	61(4.53)	27	1640	Department of Chemical Engineering, National Taiwan University	Taiwan	Microbial communities of aerobic granules: Granulation mechanisms	134
3	Van Loosdrecht, Mark C.M.	2004[b]	46(3.41)	32	4751	Department of Biotechnology, Delft University of Technology	Nether-lands	Aerobic granulation in a sequencing batch reactor	654
4	Yu, Hangqing	2005[c]	40(2.97)	27	2073	Department of Environmental Science. University of Science and Technology of China	China	Formation and characterization of aerobic granules in a sequencing batch reactor treating soybean-processing wastewater	260
5	Liu, Yu	2001[c]	36(2.67)	28	2717	School of Civil and Environmental Engineering, Nanyang Technological University	Singapore	High organic loading influences the physical characteristics of aerobic sludge granules	366
6	Mosquera-Corral, Anuska	2004[b]	27(2.00)	16	997	Department of Chemical Engineering, University of Santiago de Compostela	Spain	Aerobic granulation with industrial wastewater in sequencing batch reactors	203
7	Campos-Gomez, Jose Luis	2008[b]	26(1.93)	15	633	Department of Chemical EngineeringAdolfo Ibáñez University	Spain	Autotrophic nitrogen removal at low temperature	100
8	Cydzik-Kwiatkowska, Agnieszka	2010[a,c]	24(1.78)	11	319	Department of Environmental Biotechnology, University of Warmia and Mazury	Poland	Performance and microbial characteristics of biomass in a full-scale aerobic granular sludge wastewater treatment plant	111
9	Wan, Chunli	2013[a]	24(1.78)	16	606	Department Environmental Science Engineering Fudan University	China	Microbial communities of aerobic granules: Granulation mechanisms	134
10	Wang, Hongyu	2014[b]	24(1.78)	18	512	School of Civil Engineering, Wuhan University	China	Simultaneous nitrification, denitrification and phosphorus removal in an aerobic granular sequencing batch reactor with mixed	174

								carbon sources: reactor performance, extracellular polymeric substances and microbial successions	
11	Liu, Xiang	2013[b]	23(1.71)	16	576	Department of Environmental Science and Engineering, Fudan University	China	Microbial communities of aerobic granules: Granulation mechanisms	134
12	Tay, Stephen Tiong Lee	2002[b]	23(1.71)	21	1858	School of Civil and Environmental Engineering, Nanyang Technological University	Singapore	High organic loading influences the physical characteristics of aerobic sludge granules	366
13	Li, Jun	2013[a,c]	22(1.63)	10	276	College of Environment, Zhejiang University of Technology	China	Aerobic sludge granulation in a full-scale sequencing batch reactor	119
14	Méndez, Ramon	2004[b]	22(1.63)	14	741	Department of Chemical Engineering,University of Santiago de Compostela	Spain	Aerobic granulation with industrial wastewater in sequencing batch reactors	203

- Role in co-authorship, superscript

a First Author; b Co-author; c Corresponding author

3.4 Leading Countries and Top Institutions

Table 3 displays the total publications, single country articles, international collaborative articles, and h-index of the top 15 countries and territories in aerobic granulation studies for wastewater treatment. Based on the data retrieved from the Scopus database, in year 1997 to 2020, China produced the most articles, accounting for more than 50% of the total articles, showing China's dominance in the current aerobic granulation research. Of the total 1,347 articles published by more than 2,000 co-authors with affiliations, there were 913 single country articles, which accounted for 68% of the total publications, indicating strong collaboration within the same country, while the remaining 434 articles were internationally collaborated.

China showed a distinctive performance by owning the highest number of publications at 716, in which a total of 143 journals had the highest h-index of 56. Singapore was ranked the second most productive country, with a total of 82 publications and a h-index of 46. There is a relatively big difference in the number of publications between China and Singapore, with Singapore accounting for only 8% of the total articles in the research field, which is significantly lower compared to the contribution by China. The Netherlands, the first country that produced an article in aerobic granulation in 1997 [4], ranked third with 68 publications. The Netherlands has a major contribution in pioneering the innovative route of aerobic granules development and dominates the academic history in respect of aerobic granulation research activity worldwide. The Netherlands was also the first country that implemented a full scale industrial aerobic granulation system in wastewater treatment, which was innovated by Delft University of Technology. Singapore has made a great effort in paving the way for the growth of aerobic granulation research, when the quantity of articles published surpassed the Netherlands in year 2002, followed by China in year 2004. From 2004 to 2020, the number of articles produced by China increased dramatically with only minor fluctuations. On the other hand, Singapore experienced a significant reduction in the growth rate of article publications since year 2009. The other countries published articles with no more than 65 articles.

Despite being ranked first for the highest publishing number, China had taken up a lesser percentage for international collaboration with only 21% of collaborative papers, ranking them at the 12th spot. Among the 15 countries, it can be seen that five countries had more than 70% single-country publications, including Poland (100%), India (84.44%), Italy (80%), China (78.35%), and Singapore (74.39%). On the contrary, Germany ranked first for international collaborative publications. The country seemed to be more comparative in international collaboration when 87% of the articles published were affiliated with 10 different countries and only 13% intra-country collaborations were recorded. The United States (ranked second) and Taiwan (ranked third) showed great potential in publishing international collaborative papers, with 78.43% and 75.81% collaborative articles, respectively. The Netherlands followed in fifth place with 67.7% collaborative articles, affiliated to 25 different countries. Other countries also contributed a number of publications in the research of aerobic granulation for wastewater treatment. International research collaboration allows researchers to build and strengthen their network with other academic research groups, expand knowledge, gain new perspectives and expertise in the research field. Furthermore, research collaborations with different institutions and countries are beneficial to young researchers as it can be a tool in their career development and one of the strategies to enhance the research impact and productivity.

The publication numbers of each institution indicates the level of their research contribution in the field of aerobic granulation in wastewater treatment. In Table 4, the total publications, total citations, single-institute publications, and inter-institutionally collaborative publications of the top 15 most productive academic institutions were shown and analysed. Out of 694 articles, 236 articles (34%) were single-institute publications, and 458 articles (66%) were inter-institutionally collaborative publications. Based on Table 3, China has taken eight places out of the top 15 academic institutions, showing their strength as the most productive country and remarkable dominance in the current aerobic granulation field. Harbin Institute of Technology, China ranked first with the highest total publications (98) and achieved the most inter-institutionally collaborative publications (92). A total of 98 articles published by Harbin Institute of Technology, China were affiliated to 45 different institutions worldwide and 87 of the total articles were linked to 34 institutions from China. Therefore, it is justified that in Table 3, China has 78.3% of single country publications, as they have more collaboration articles between academic institutions in China compared to international collaborations. Further to that, it is clearly seen that the leading position of China as the most productive country is probably due to the contribution and involvement of many institutes in China that made great improvement in the quantity of articles, compared to other countries. Nanyang Technological University, Singapore has the second most articles (80) of the total 5,203 citations, with the highest single institute publications (75%) and the least inter-institutionally collaborative publications. The highest number of total citations achieved by Nanyang Technological University, Singapore can be attributed to the great influence and authority of the most prolific author, J.H. Tay (Table 2), in respect to the aerobic granulation research field. According to the Scopus database, 65 out of 80 publications published by Nanyang Technological University, Singapore, with 35 most cited articles, involved J.H. Tay as the co-author. Although this academic institution has the lowest ranking in inter-institutional collaborative publications of only 25%, the number of total citations were significantly higher than Harbin Institute of Technology, China. It is analysed that Singapore tends to focus more on the quality of the publications, while China more likely focused on the growth rate of the quantity of publications.

Table 3. Top 15 most productive countries/territories based on total number of publications.

No	Country	TP$_C$	Single-Country Publications (SCP)		International- Countries Collaborative Publications (ICCP)		h-index
			SCP (n)	SCP (%) / rank	ICCP (n)	ICCP (%) / rank	
1	China	716	561	78.35 (4)	155	21.65 (12)	59
2	Singapore	82	61	74.39 (5)	21	25.61 (11)	46
3	Netherlands	68	22	32.35 (11)	46	67.65 (5)	39
4	Canada	62	35	56.45 (6)	27	43.55 (10)	21
5	Taiwan	62	15	24.19 (13)	47	75.81 (3)	27
6	Spain	59	30	50.85 (9)	29	49.15 (7)	29
7	United States	51	11	21.57 (14)	40	78.43 (2)	26
8	Malaysia	46	25	54.35 (7)	21	45.65 (9)	17
9	India	45	38	84.44 (2)	7	15.56 (14)	15
10	Japan	41	10	24.39 (12)	31	75.61 (4)	20
11	Italy	40	32	80.00 (3)	8	20.00 (13)	19
12	Brazil	39	21	53.85 (8)	18	46.15 (8)	17
13	Poland	36	36	100.00 (1)	0	0.00 (15)	13
14	Australia	33	12	36.36 (10)	21	63.64 (6)	22
15	Germany	32	4	12.5 (15)	28	87.5 (1)	18

TPc: Total Publications of a given country

Nonetheless, collaborations between institutions is also one of the strategies for academic institutions to obtain higher world ranking positions, as in the Netherlands. Delft University of Technology, the Netherlands ranked third in total publications (58) and had outstanding inter-institutional collaborative publications of 41 out of a total of 58 articles. Delft University of Technology also possessed the second rank in total citations ranking of 4,990, showing great teamwork of the research group of the author M.C.M, Van Loosdrecht (top 3 most prolific author) to strengthen the influences in the aerobic granulation field for wastewater treatment. It is noted that 46 articles published by Delft University of Technology were co-authored by M.C.M, Van Loosdrecht, which are affiliated to 36 different institutions. In order for the institute to achieve a higher ranking position and receive a higher number of citations, it is necessary to reinforce research work among single-institute publications and Inter-Institutionally Collaborative Publications in promoting the aerobic granulation for wastewater treatment research fields in the future

Table 4. Top 15 most productive academic institutions based on total number of publications.

No	Academic Institutions	TP$_I$	Single-Institute Publications (SCP)		Inter-Institutionally Collaborative Publications (ICP)		Total Citations
			SIP (n)	SIP (%) / rank	ICP (n)	ICCP (%) / rank	
1	Harbin Institute of Technology, China	98	6	6.12	92	1	1459
2	Nanyang Technological University, Singapore	80	60	75	20	2	5203
3	Delft University of Technology, Netherlands	58	17	29.31	41	3	4990
4	Beijing University of Technology, China	56	25	44.64	31	4	380
5	National Taiwan University, Taiwan	55	4	7.27	51	5	1535
6	University of Science and Technology of China, China	49	18	36.73	31	6	2152
7	Chinese Academy of Sciences, China	43	4	9.30	39	7	800
8	Beijing Normal University, China	43	29	67.44	14	8	806
9	Zhejiang University of Technology, China	36	10	27.78	26	9	373
10	Fudan University, China	34	1	2.94	33	10	866
11	University of Calgary, Canada	31	18	58.06	13	11	516
12	Universiti Teknologi Malaysia, Malaysia	29	16	55.17	13	12	380
13	Universidad de Santiago de Compostela, Spain	29	15	51.72	14	13	893
14	Shandong University, China	27	13	48.15	14	14	699
15	National Taiwan University of Science and Technology, Taiwan	26	-	0.00	26	15	593

•   TPi: Total Publications of a given institution

3.5 Analysis Of Co-Authorship

The research collaboration among countries on aerobic granulation in wastewater treatment is displayed in Figure 2. The close distance between two countries appear on the visualization map, indicating the great number of joint research projects conducted by two countries. It should be noted that the thickness of the line connecting two countries denotes the strength of their bonds. In the VOSviewer software, the minimum number of documents required by a country was set at one. A total of 50 countries had made contributions in the field of aerobic granulation research for wastewater treatment, which was led by Asia with 16 countries. The results of co-authorship revealed that the Netherlands was the most affiliated country, including 57 occurrences of co-authorship with 25 different countries/territories. This is followed by China (18 links, 172 co-authorship), the United States (18 links, 56 co-authorship), France (15 links, 20 co-authorship), the United Kingdom (14 links, 25 co-authorship), Canada (11 links, 42 co-authorship), Spain (11 links, 32 co-authorship), Brazil (11 links, 24 co-authorship), Malaysia (11 links, 22 co-authorship), and Germany (10 links, 31 co-authorship). The remaining 40 countries have less than 10 international collaborations in aerobic granulation research field. Meanwhile, Poland, Hungary, Latvia and Romania are not affiliated with any of the countries in publishing articles. China and Taiwan had the most collaborative articles, with a link strength of 41, demonstrating their strongest collaboration network in aerobic granulation research field. The second strongest collaborations (link strength of 22) were between China-USA and China-Japan. China has established links with countries not just in Asia, but also in Europe and North America. The number of articles published by China in collaboration with other countries has bolstered China's current position as the world's top ranking in this field.
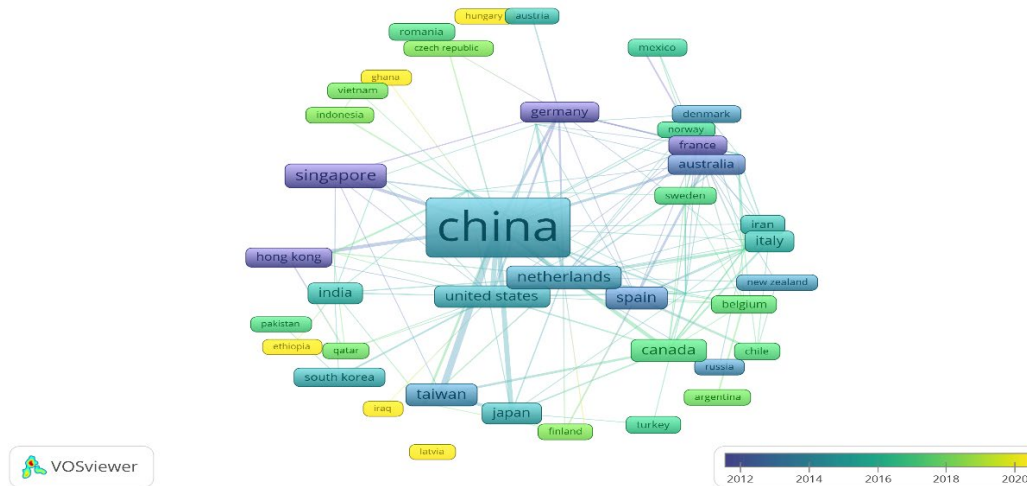
Figure 2. A bibliometric map of co-authorship analysis with overlay visualization mode.

3.6 Analysis of Author Keywords

The network visualization map of co-occurrence of author keywords is displayed in Figure 3. The least number of occurrences of a term was set as three. Of the 2,454 keywords, 265 met the proposed threshold. The most commonly used author keywords of "AGS", "SBR" and "Wastewater Treatment" were ignored, as they were considered as topic words in the current study. The most occurrence keywords after excluding AGS", "SBR" and "Wastewater Treatment" was EPS with 157 occurrences and 101 links to other keywords. This is followed by the keyword nutrient removal (136 occurrences, 84 links), simultaneous nitrifications and denitrifications (SND) (109 occurrences, 83 links), microbial community (106 occurrences, 87 links), aerobic granules stability (50 occurrences, 49 links), biodegradation (42 occurrences, 42 links), and activated sludge (37 occurrences, 38 links).

The keyword EPS with average publication year 2015 was repeated 157 times and linked to 101 other keywords. EPS had the highest correlations with the term AGS (129 link strength). In many studies, it was illustrated that EPS is one of the major factors influencing the formation of aerobic granules. The keyword EPS was also closely related to terms "microbial community" and "quorum sensing" by 18 publications and 8 publications, respectively. "Microbial community" such as Brachymonas, Zoogloea, Thauera, Rhodocyclaceae, Xanthomonadaceae, Sphingomonadaceae, Meganema and Devosia are well known to be a good EPS producer in the formation of AGS. Furthermore, the production of EPS was also regulated by "quorum sensing", with Acyl homoserine lactone (AHL) being one of the most important auto-inducers involved in quorum sensing. According to Tan et al. [15], higher AHL concentrations were responsible for increased EPS synthesis. In Figure 3, it was found that the keyword "protein", "polysaccharides" and "hydrophobicity" were also associated to EPS. Protein (PN) and polysaccharides (PS) are the main components of EPS, both of which are essential for the formation of compact and denser aerobic granules. Wang et al. [16] found that EPS content was closely linked to hydrophobicity. EPS fractions comprised of hydrophobic and

hydrophilic groups, with hydrophobic groups containing more protein and polysaccharides being hydrophilic. Besides that, 12 articles were published containing both keywords EPS and "aerobic granules stability". EPS are responsible for the physical properties of AGS and maintaining the structural stability of AGS. High EPS secretion may enhance the stability of aerobic granules, whereas insufficient EPS content may result in the formation of a weak AGS structure. In addition, the keyword "Adsorption" and "Bio-sorption" was linked to EPS with a total of six link strength. Previous studies have regarded the role of EPS as an effective adsorbent especially on the removal of heavy metal in wastewater. The keyword "heavy metal removal" had been repeated three times along with "adsorption" and "bio-sorption". In many years, AGS have shown their excellent efficiency in removing many heavy metals through bio-sorption/adsorption. "Cr(vi)" and "Pb2+" are among heavy metals related to "bio-sorption" with a total of eight occurrences. A study by Dong Wei et al. [17] demonstrated that EPS in AGS successfully removed methylene blue (MB) from dye wastewater during the bio-sorption process. The author further revealed that AGS was effective in the removal of heavy metal due to the presence of PN in EPS that is responsible for the bio-sorption of heavy metals such as Zn (II), Pb (II) and Cu (II) [18,19,20].

Keywords containing "nutrient removal" were encountered 136 times, showing the excellent performance of AGS in removing biological nutrients such as Nitrogen (N) and Phosphorus (P), in various types of wastewaters. Nutrient removal was linked to 84 other keywords, where it was closely associated with the central theme "AGS" and "SBR" with a total link strength of 138. Meanwhile, the keyword "SND" appeared 104 times in the VOSviewer software and linked to 83 keywords. A total of 15 articles were discovered containing both keywords "Nutrient removal" and "SND". Simultaneous nitrification and denitrification (SND) is a process required to completely remove nitrogen, phosphorus, and ammonium from the system. The top keywords associated with "nutrient removal" and "SND" were "nitrous oxide", "AB-AGS", "particle size", "dissolved oxygen", "carbon sources", and "microbial community". Keywords such as "dissolved oxygen", "carbon

sources", "microbial community", and "particle size" were among the parameters that influenced simultaneous nitrification-denitrification process, with a total link strength of 10 [1,5]. Total nitrogen removal in the SND process is highly dependent on oxygen concentration; thus, it is important to control the dissolved oxygen (DO) level. A high DO level is required to sustain nitrifications, while a low DO level is required during the denitrification process. In five publications, researchers investigated the effect of "carbon sources" on biological nutrient removal and SND processes. Carbon sources, including acetate and glucose, act as an electron donor during the denitrification process. At the denitrification stage, acetate produces "PHB" (poly-β-hydroxyalkanoates) as intracellular storage polymer and replaces the depleted carbon. The keyword "PHB" was repeated five times in conjunction with "SND". A higher SND rate and excellent simultaneous biological nutrient removal efficiency could be achieved with the aid of electron donors. The results showed that "Microbial community" is also linked with "nutrient removal" and "SND". "Microbial Community" co-occurred with slow growing bacteria "AOB", "NOB", "PAO", and "GAO". AOB, ammonium oxidized bacteria (AOB) act as nitrifying bacteria which are responsible to convert ammonium to nitrate, while nitrite oxidizing bacteria (NOB) act as denitrifying bacteria that convert nitrate to nitrogen gases. The denitrification process mainly produces "nitrous oxide", a gaseous nitrogen oxide that has a harmful impact to the environment. It was observed that the keyword "anammox", a slow growing bacteria, which have been considered as promising technology in nitrogen removal, exhibited close relations with "nitrous oxide". "Anammox" was repeated 55 times and linked with 31 keywords. "Anammox" co-occurred with "partial nitrification", showing the capabilities of anammox bacteria to shorten the process so that the emission of "nitrous oxide" during denitrification can be avoided and achieve excellent total nitrogen removal. Phosphorus accumulating organisms ("PAO") was responsible for the removal of phosphorus. However, glycogen-accumulating organisms ("GAO") that coexist with PAOs may take up food sources (VFAs) from the PAOs, resulting in less phosphorus release by the PAOs in the anaerobic zone. A study by de Kreuk et al. [21] revealed that "particle size" of granules affects the removal efficiency of total nitrogen.

The keyword "microbial community" had been mentioned 106 times, linked with 87 keywords with average publications in the year of 2015. The keyword was frequently linked with "AGS", "EPS", "nutrient removal", "SND" and "SBR", summed to a total of 129 publications. As discussed in the previous paragraph, it is justified that the "microbial community" plays a significant role in "nutrient removal" especially in "SND" processes. The keyword co-occurred with "olr", "aeration rate", "settling time ratio", "f/m ratio", "starvation", and "quorum sensing". This represents the factors influencing the microbial community. Other keywords that correlated with "microbial community" included "FISH", "DGGE", "PCR-DGGE", and "high-throughput sequencing" indicating the technique used to analyse the composition of the microbial community. The keywords "low-strength wastewater", "piggery wastewater", "saline wastewater", and "livestock wastewater" were discovered to be associated with microbial communities. This demonstrates the significance and influence of the microbial community in various types of wastewaters including low and high strength wastewaters. The next most popular keyword

was "aerobic granules stability", with 50 occurrences, 49 links and an average publication year of 2014. There are several factors affecting the aerobic granules formation and granules stability. The keywords "selection pressure", "olr", "seed sludge", "f/m ratio", "carbon source", and "aeration rate" were among the operational conditions that contributed to the successful granules development and maintaining the structural stability of granules. The keyword "filamentous microorganism" was linked with "aerobic granules stability", with three link strengths. The excessive growth of filamentous microorganisms in the reactor caused an unstable operation, resulting in the loss of granule stability [22]. Therefore, the application of strong "shear force", in which the keyword appeared 10 times, is essential to inhibit the overgrowth of filament bacteria. Both keywords "Storage" and "continuous flow reactors" were closely related to "aerobic granules stability", demonstrating the methods with higher potential in maintaining the aerobic granules stability over long term operations.

Based on the co-occurrence analysis, it is observed that the hot topics addressed by many researchers on the AGS field were (i) factors influencing the development of AGS, (ii) AGS removal performance in wastewater treatment, (iii) efficiency of the AGS system in simultaneous nitrification and denitrification processes, and (iv) the structural stability of AGS developed in SBR. In the bibliometric map, the keywords "microalgae", "AB-AGS", "bio-char", "petroleum wastewater", "oxytetracycline", "antibiotic wastewater", and "tomato paste processing wastewater" exhibited recent average publication in the year of 2018 and 2019. This implies that these keywords are relatively new in the AGS research fields which can be focused for further investigation.

4. Limitations of Study

A bibliometric analysis was conducted to demonstrate the current research trends of AGS in wastewater treatment. Like most other bibliometric analyses, several limitations are inevitable. First, this study only considered the Scopus web to retrieve the bibliographic data. Regardless of the fact that Scopus is one of the largest sources, there are other databases that publish relevant works in the AGS research field, where the data outputs may have gone unnoticed and excluded. In addition, using multiple databases is recommended as it would be beneficial for more extensive bibliometric studies. Second, this analysis only focused on data outputs from research articles. The exclusion of other types of documents including reviews, proceeding papers, book chapters and books could eliminate some critical information and contributions to the field. Therefore, including these documents for future studies may be considered. Nevertheless, the Scopus database is extensively used by scholars for production of high-quality bibliometric analyses since it has numerous features and is more accessible than other databases. Third, bibliometric studies of the AGS field need in-depth analysis, for example a detailed evaluation on the microbial factors affecting granulation, effective techniques used by researchers to accelerate biogranules development, and the characteristics of developed aerobic granules. Despite that, a bibliometric analysis enables researchers and scientists to make great efforts to improve the application of AGS in wastewater treatment, by analysing the prevalent topics and hotspots in AGS studies.
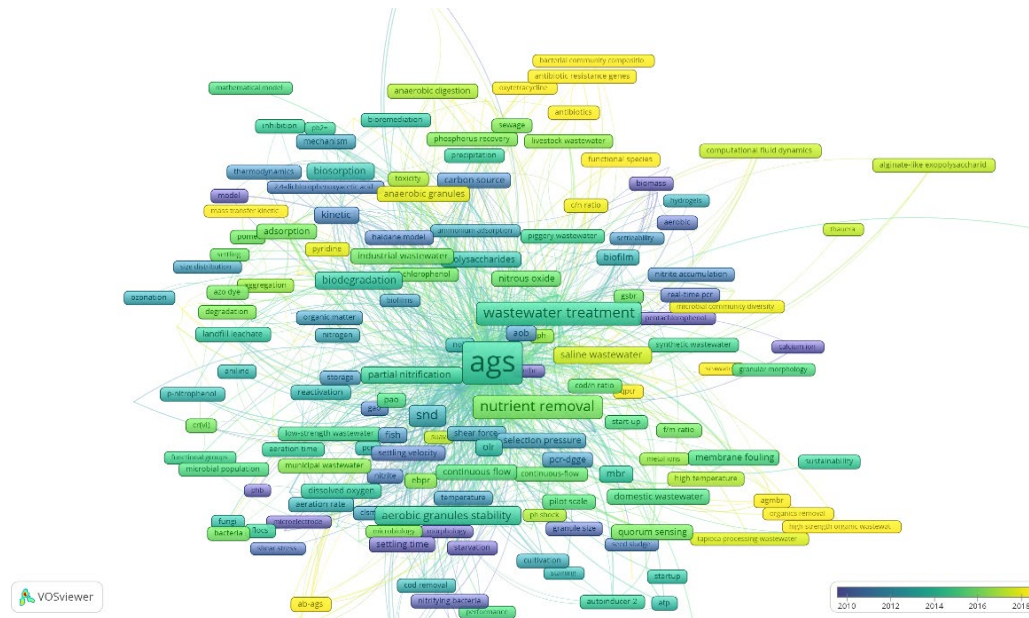
Figure 3. A screenshot of the bibliometric map created based on author keywords co-occurrence with overlay visualization mode.

5.0 CONCLUSION

The bibliometric analysis provides significant information on AGS research trends throughout the period from 1997 to 2020. A total of 1,347 articles were published in 146 journals, which revealed the rapid development of AGS research in wastewater treatment over the past 20 years. Bioresource Technology, Environmental Science, the China and Harbin Institure of Technology dominated in journals, subject categories, countries, and academic institutions. The Netherlands was the most active collaborator, accounting for 67% of international collaborative articles affiliated to 25 different countries. This study also proposed several areas for future AGS research including a new approach to accelerate the AGS formation, such as addition of bio-char in treating petroleum wastewater, the potential of Microalgal-bacteria granular sludge (MBGS) to replace AGS in wastewater treatment and the performance of AGS in treating emerging wastewaters such as tomato paste processing wastewater and the removal of oxytetracycline in antibiotic wastewater.

Acknowledgement

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