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Discovering future research trends of aerobic granular sludge using bibliometric approach

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ABSTRACT

The advantageous characteristics of aerobic granular sludge (AGS) have led to their increasing popularities among academics and industrial players. However, there has been no bibliometric report on current and future research trends of AGS. This study utilized the available reports of AGS in the Scopus database for comprehensive bibliometric analyses using VOSviewer software. A total of 1203 research articles from 1997 to 2020 were analyzed. The dominance of the Netherlands and China were revealed by the high number of publications and citations. Nevertheless, the Netherlands exhibited higher average citation per article at 76.4. A recent process of AGS involving biochar and algal addition were also identified. Meanwhile, the application of AGS for antibiotic containing wastewater as well as possibility of resource recovery were recently reported and was expected to expand in the future. It was suggested that application of AGS would develop further along with the development of sustainable wastewater treatment process.

1. Introduction

Aerobic granular sludge (AGS) system has gained popularity in wastewater treatment systems due to its advantageous properties leading to significant reduction in energy requirement and land footprint while achieving better treatment efficiency (Nancharaiah and Reddy, 2017; Pronk et al., 2015). The unique characteristics of AGS allow fast separation of sludge and treated wastewater in a single reactor due to the high settleability of aerobic granules (Zhang et al., 2016). This results in less sludge wastages ended being disposed into the landfill (Sarma and Tay, 2018). Moreover, recent studies demonstrated the possibilities of resource recovery processes from AGS (Zhang et al., 2020). Over the last decade, AGS system has been implemented in several full-scale treatment plants due to the intensive research and innovation by academic and industrial players worldwide (Li et al., 2014; Świątczak and Cydzik-Kwiatkowska, 2018).

Reports on AGS are available in book chapters, conference proceedings, review and research articles through many databases, such as Scopus, Web of Science, and PubMed. The enormous amounts of documents may be overwhelming and making it difficult to identify the current focus and research gap in the field. Hence, a bibliometric analysis may be useful to quantitatively analyze the available documents in a database to derive research trends for future references. Zheng et al. (2018) has highlighted the bibliometric analyses of granular sludge by using bibliographic data from Web of Science database, in which documents regarding anaerobic and AGS were analyzed. Nevertheless, investigation focusing on AGS system has not been addressed deeper.

This study aims to present the distribution of research articles of AGS in terms of the authors of publication, countries and institutes. The collaboration of countries worldwide was also highlighted in this article. Moreover, the keywords correlation and co-occurrences were elucidated followed by discussion on current and potential hot topics in AGS. This study has analyzed the available publications on AGS from Scopus database whereby the available data was analyzed using VOSviewer.

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VOSviewer is a software for analyses and visualization of bibliometric maps by utilizing the exported bibliographic data. Scopus was specifically chosen as it is recognized as the largest abstract and citation database (Aghaei Chadegani et al., 2013). It is expected that this study will be beneficial for researchers, academicians, policymakers and industries to discover the future prospects and potentials of this field.

2. Methodology

2.1. Data sources and search strategy

Methodology of data collection was adopted according to Md Khudzari et al. (2018). Bibliometric data was collected from the Scopus database on July 5, 2021, covering for documents on AGS from 1997 to 2020. The query string used for the search was: TITLE-ABS ("aerobic granular sludge" OR "aerobic granul* sludge" OR "aerobic granulation") OR AUTHKEY ("aerobic granular sludge" OR "aerobic granul* sludge" OR "aerobic granulation") AND (EXCLUDE (PUBYEAR, 2021)), which resulted in 1484 document results, comprising of various document's type, including review paper, conference proceeding and book chapter. In order to specifically analyze the research trends, this study was focusing on research articles. Therefore, review-based documents were excluded from the results by using filter feature in the Scopus search engine. In addition, to ensure no review articles were included in the bibliometric analyses, potential review articles were identified by screening the title, abstract and keywords of all document results. The articles containing terms such as review, highlight, progress, advance (d), etc. were ruled out from the data. Exclusion of these review articles were performed by identifying their EID (Scopus document identification number) and applying the field codes 'AND NOT' in Scopus advanced search. The final data sources comprised of 1203 document results. The citation and bibliographical information, as well as the abstract and author keywords from the document results were exported into CSV file for further analyses. The process of data mining and report elimination was summarized in Fig. 1.

2.2. Bibliometric analysis

The exported data from the Scopus database was analyzed using VOSviewer version 1.6.16 developed by Center for Science and Technology Studies, Leiden University, the Netherlands. The maps created using VOSviewer in this study were based on countries co-authorship and author keywords co-occurrences. The bibliometric map shows relation between 2 or more items, in which every link is represented with a certain strength value. A higher link strength indicates stronger relation between each item. All bibliometric maps in this study are available online and accessed through link provided in the respective figures. Moreover, other data analyses were conducted using Microsoft Excel 365.

2.2.1. Analyses of bibliographic data

The data obtained from search string was subjected to further analyses of relevant subject areas, most productive journals, countries and institution, along with identification of prolific authors. The document results were filtered according to 'source title' to identify the top producing journals. Meanwhile, related subject area, most productive countries and authors were analyzed using the feature 'Analyze search results'. Information on top producing countries was divided into two categories, namely total publication and single country publication (SCP). The amount of SCP was retrieved by using the operators 'AND NOT' and field codes 'AFFILCOUNTRY', resulted in documents published by single country. In addition, the identification of prolific authors was performed using Scopus author ID to minimize the possibility of redundancy of the same author. For example, Van Loosdrecht, M. C. M appeared twice in the list of authors, despite having the same Scopus author ID.

2.2.2. Analysis of countries co-authorship

A total of 48 countries were included in the analysis of countries co-authorship. The analyses were performed based on the exported data file, and minimum number of publications per country was set to 1. The affiliated countries were classified into five groups according to the continent, namely Asia, Europe, America, Africa and Oceania. Countries under the same groups are represented with the same color in a bibliometric map. Relationship between two countries is indicated by a line and the link strength represents the number of collaborated articles between these countries.

2.2.3. Analysis of keyword co-occurrence

The exported data from the Scopus database included a total of 2363 author keywords. However, data on author keywords were found to be redundant. Thus, data cleaning (merging similar keywords) was performed, resulted in 94 final keywords. The minimum number of occurrences were set to five. Overlay visualization mode in VOSviewer was selected to display the map according to the average publication year of each keyword. The relation between two keywords are also represented as link strength, whereby the value indicates the number of documents containing the two respective keywords.

3. Results and discussion

3.1. Publication outputs

The data collected from the designed query string resulted to 1484 articles within a time period of 23 years starting from 1997 until 2020. The articles predominantly consisted of research articles, representing

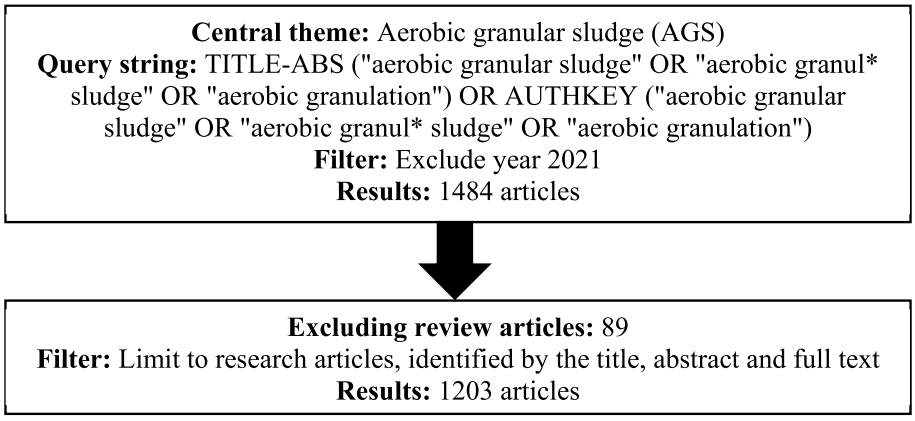

Fig. 1. Flowchart of data collection for research articles in AGS.

84% (1242) of the total results. The remaining documents include conference proceedings (145), review articles (51), book chapters (11) and others. The bibliometric analyses in this study focused on empirical research to clearly identify and justify the past, current and future research trends of AGS. As a result of excluding other types of documents, 1203 research articles were collected and analyzed using VOSviewer.

The growth on number of research articles throughout the year is depicted in Fig. 2. The first report on AGS was published in 1997 by Morgenroth et al. and the number of publications was not significant until 2002, whereby there were less than 10 cumulative publications on AGS. The number of publications moderately increased from 2003 to 2008, in which 27 articles were published annually, on average. The trend significantly increased from 2009 until 2020. Generally, from 1997 to 2020, the annual publications significantly increased from 1 to 160 documents. The growth on cumulative publication may be expressed based on power equation $y = 0.1979 \times {}^{2.6688}$, with $R^2 = 0.998$, whereby y is the cumulative publication and x is year since 1997. Thus, based on the model equation, the annual publication in 2027 is expected to increase to 1732 publications. However, the actual number of published articles has exceeded the prediction using generated equation.

It was found that 978 documents were published in English (81%), followed by 218 articles in Chinese (18%). Meanwhile, the other languages used were Polish (3), Portuguese (3), German (1), Malay (1) and Spanish (1). The most cited article was entitled "Aerobic granulation in sequencing batch reactor", which was published in 1999 in Water Research and has received 625 citations. This was followed by an open access article, published in 2005 in journal of Applied Environmental Microbiology, entitled "Composition and distribution of extracellular polymeric substances in aerobic flocs and granular sludge" with 545 citations. The earliest publication in 1997, "Aerobic granular sludge in sequencing batch reactor" has received 477 citations. Within all published articles, only 193 articles (16%) were published in open access journals. Young and Brandes (2020) suggested that publication in open access journals may receive higher number of citations as these articles are freely available for readers.

3.2. Subject areas and preferred journals

A 1203 research articles were categorized into 19 subject areas in the Scopus database. The 5 most relevant subject areas are shown in Fig. 3, namely 'Environmental Science' (923, 77%), 'Chemical Engineering', 'Biochemistry', 'Engineering' and 'Energy'. The subject area of 'environmental science' has received the highest number of citations (19,522) in 2020, which was distantly followed by the remaining subject areas. Although the subject area of 'chemical engineering' and 'biochemistry' were first included in 2001, their publication numbers increased significantly by 2020, to 366 and 202, respectively.

As the research on AGS expands over decades, more general subject areas, such as 'Engineering' emerged in 2004. This growth may be related to the emerging studies on operational parameters of AGS system, such as settling time, organic loading rate, pilot and full-scale operations, etc. (Ab Halim et al., 2015; He et al., 2020b; Jiang et al., 2019; Val del Río et al., 2012). The innovation on AGS related with 'energy' was started in 2006 and has significantly increased from 96 to 121 in 2017 when the United Nation (UN) launched the Sustainable Development Goals (SDGs), which consisted of 17 inter-related goals, including those associated with water and sanitation (SDG 6) and energy (SDG 7). It is predicted that the subject area of 'energy' will grow further in the future as the research focus shifts to energy-efficient wastewater treatment process or resource recovery to minimize energy consumption (Malamis et al., 2015).

The articles on AGS have been published in 160 different journals and the 10 highest producing journals are summarized in Table 1. Bioresource Technology has produced the highest number of research articles of 145 (12%). However, Water Research accounted for the highest citation number in 2020, which was 6016 and the highest CiteScore2020 of 15.6. Water Research has also published the first article on AGS in 1997 and the most cited article published in 1999. The number of publications was closely followed by Huanjing Kexue/Environmental Science by Chinese Publisher Science Press. Despite having a relatively lower total citation number of 267 and CiteScore2020 of 2.4, this journal has published 82 research articles on AGS. Furthermore, more than 1000 citation number has been received by journal of Water Science and Technology, Applied Microbiology and Biotechnology, Chemosphere and Journal of Hazardous Materials. In addition, the top 10 journals

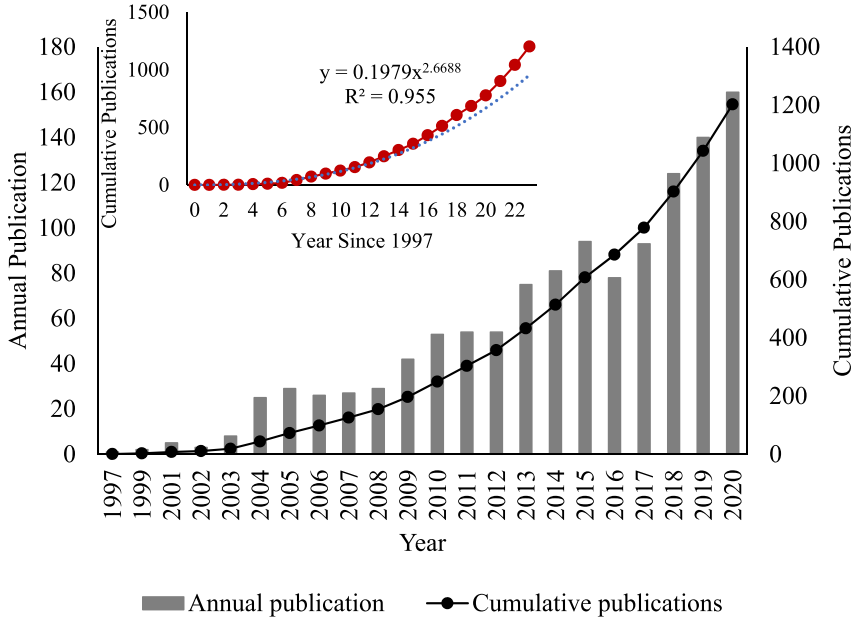

Fig. 2. The annual and cumulative number of research articles on AGS from 1997 to 2020 (Inside: model on growth tendency of cumulative publication, whereby the dash line shows the prediction based on the model equation).

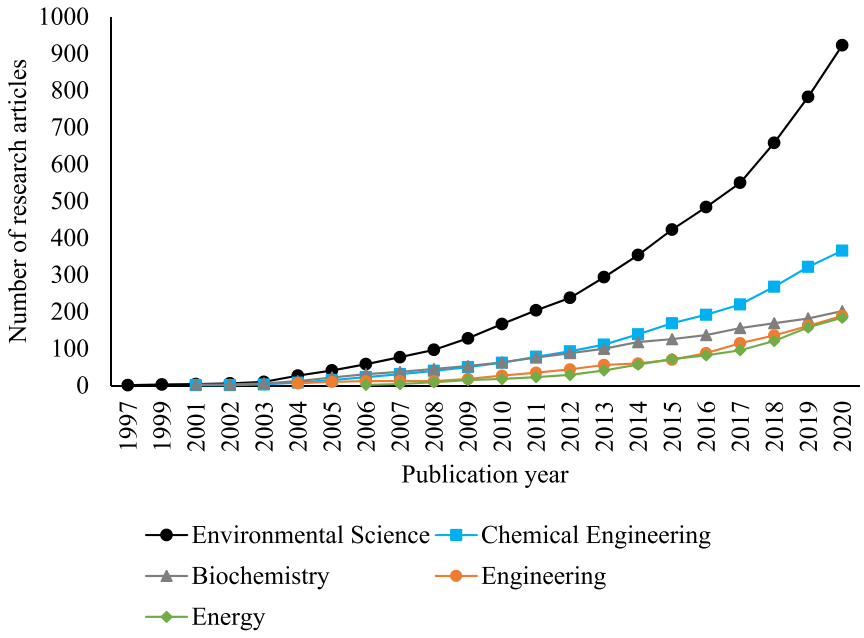

Fig. 3. The number of published research articles associated with the top 5 subject areas in AGS over the years.

Table 1
The list of 10 most productive journals in publishing research articles on AGS.

No.	Journal name	Total Publication	Percentage publication	Total citations	CiteScore 2020	Most cited article	Citation number	Publisher
1	Bioresource Technology	145	12.1	4042	14.8	Aerobic granulation with brewery wastewater in a sequencing batch reactor	134	Elsevier
2	Water Research	85	7.1	6016	15.6	Aerobic granulation in a sequencing batch reactor	611	Elsevier
3	Huanjing Kexue/ Environmental Science	82	6.8	267	2.4	Profiles of zeta potential and EPS in granulation process of aerobic sludge	13	Science Press
4	Water Science and Technology	47	3.9	1022	3.3	Selection of slow growing organisms as a means for improving aerobic granular sludge stability	243	IWA Publishing
5	Applied Microbiology and Biotechnology	44	3.7	1846	7	The effects of shear force on the formation, structure and metabolism of aerobic granules	370	Springer Nature
6	Chemosphere	35	2.9	1083	10.1	Formation and instability of aerobic granules under high organic loading conditions	192	Elsevier
7	Zhongguo Huanjing Kexue/China Environmental Science	35	2.9	81	1.6	Effect of anaerobic/aerobic alternative operating strategy on the formation of granular sludge in a sequencing batch reactor	10	Zhongguo Huanjing Kexue Xuehui
8	Desalination and Water Treatment	34	2.8	122	1.6	Culture of denitrifying phosphorus removal granules with different influent wastewater	14	Desalination Publications
9	Journal of Hazardous Materials	32	2.7	1034	13.4	Biosorption of Acid Yellow 17 from aqueous solution by non-living aerobic granular sludge	125	Elsevier
10	Environmental Technology United Kingdom	29	2.4	326	4.2	Substrate concentration-independent aerobic granulation in sequential aerobic sludge blanket reactor	101	Taylor & Francis

were coming from different publishers, including Elsevier, Science Press, Springer Nature and Taylor & Francis. Of the top 10 journals, 5 journals are from the United Kingdom, 2 from China, 1 from Germany, 1 from the United States and another 1 from the Netherlands.

3.3. Author performances

The analysis of the authors is beneficial to explain the scientific contribution of a research group in a particular field. The 10 most prolific authors are listed in Table 2, along with the first publication and total publication number on AGS, and *h*-index of the authors. Tay Joohwa from University of Calgary, Canada, was leading with 70 research articles, *h*-index of 81 and total citation per 2020 of 3828. The author of the first published research article on AGS, van Loosdrecht Mark, followed as the second highest producing author. Nevertheless, this author has received the highest number of citations per 2020 at 6005 and the highest *h*-index of 128. His affiliation, Delft University of the Netherlands, is also known as the innovator in implementing an AGS

Table 2
The top 10 prolific authors in AGS.

No.	Name	Scopus author ID	1st publication	Total publication	h-index	Total citation	Current affiliation	Country
1	Tay, Joohwa	7,102,544,287	2001	70	81	3828	University of Calgary	Canada
2	van Loosdrecht, Mark	7,004,463,801	1997	60	128	6005	Delft University of Technology	Netherlands
3	Lee, Duu-Jong	7,406,667,455	2008	35	87	937	City University of Hong Kong	Hong Kong
4	Liu, Yu	7,410,217,127	2001	34	65	2673	Nanyang Technological University	Singapore
5	Wei, Dong	55,701,221,600	2012	24	29	544	University of Jinan	China
6	Du, Bin	56,364,480,400	2012	23	63	542	University of Jinan	China
7	Cydzik-Kwiatkowska, Agnieszka	16,318,767,300	2010	22	18	258	Uniwersytet Warminsko-Mazurski w Olsztynie	Poland
8	Wei, Qin	7,201,692,981	2012	22	68	481	University of Jinan	China
9	Li, Jun	56,550,067,300	2014	20	22	273	Zhejiang University of Technology	China
10	Mosquera-Corral, Anuska	6,603,261,499	2004	20	37	711	Universidad de Santiago de Compostela	Spain

No.	Countries	Total publication	Single country publication (SCP)	Percentage SCP	Most productive institution	Total institution publication
1	China	674	561	83.2	Harbin Institute of Technology	85
2	Netherlands	75	24	32.0	Delft University of Technology	23
3	Canada	59	34	57.6	University of Calgary	21
4	United States	54	12	22.2	University of Washington	3
5	Singapore	52	45	86.5	Nanyang Technological University	45
6	Spain	43	20	46.5	Universidade Santiago de Compostela	13
7	Brazil	41	21	51.2	Universidade Federal de Santa Catarina	8
8	Malaysia	40	22	55.0	Universiti Teknologi Malaysia	17
9	Taiwan	38	12	31.6	National Taiwan University	9
10	Italy	33	28	84.8	Università degli Studi di Palermo	14

Fig. 4. The top 10 most productive countries producing research articles in AGS.

system in a full-scale wastewater treatment plant under the commercialized name Nereda (van Dijk et al., 2020).

The following list of most prolific authors was dominated by authors from Asia. Lee Duu-Jong has published 35 research articles in AGS and has *h*-index of 87 from 937 total citations. In addition, Liu Yu from Nanyang Technological University has received higher citation number of 2,673, resulting in *h*-index of 65. There were 3 authors from University of Jinan, China, namely Wei Dong, Du Bin and Wei Qin with 24, 23 and 22 total publications, respectively. Until July 2021, approximately 160 authors were reported to have published research articles in the field of AGS.

3.4. Performance of countries on co-authorship

Data on leading countries and institutions in the field of AGS is shown in Fig. 4, whereby 10 most productive countries are listed along with the top producing academic institution of each country. Among the top 10 countries, 4 are in Asia, 3 are located in America and the remaining 3 are located in Europe. China has significant lead compared to the other countries with a total of 674 research articles. An 83% of the total publications were SCP, indicating strong intra-country publication in China. Other countries with higher percentage of SCP included Singapore and Italy with 86% and 85%, respectively. From a total of 674 research articles, 85 articles were associated with Harbin Institute of Technology, which is a public research university in China. Nevertheless, Harbin Institute of Technology was not affiliated in the list of most prolific authors in Table 2.

Following China, the Netherlands has published 75 research articles, in which 23 articles were affiliated to Delft University of Technology. Delft University of Technology has successfully pioneered the application of AGS system in full-scale treatment plants by close collaboration with the Royal HaskoningDHV. This has proven the significant contribution of their research group towards innovation and commercialization ofAGS. Canada followed in the third place with 59 published research articles, whereby 21 of them were published by University of Calgary. Meanwhile, other countries included the United States, Singapore, Spain, Brazil, Malaysia, Taiwan and Italy closely followed in the list. Some of the most productive universities were also listed in the top 200 universities (QS ranking) 2021, namely Nanyang Technological University (rank 13), Delft University of Technology (rank 57), National Taiwan University (rank 66), University of Washington (rank 72) and Universiti Teknologi Malaysia (rank 187). This demonstrates that AGS has been one of the research focus of the top universities.

The comparisons of the top 2 leading countries, China and the Netherlands are depicted in Fig. 5. It is shown that the Netherlands has pioneered the research of AGS since 1997. However, in 1999, China began to venture into similar research area focusing on AGS studies and starting from 2005, cumulative publications from China were 3 times higher than the Netherlands. This significant increase may be contributed by the major economic development in China, which led to higher investment for research and education (Loosdrecht and Brdjanovic, 2014). Nevertheless, significant gaps remain between China and the Netherlands in terms of average citation received per article. Despite the extensive number of publications, China maintains an average of 14 citations per article, while the Netherlands received an average of 76 citations per article, which is 5.4 times higher than China. The results were consistent with the report by Zheng et al. (2018), which calls for an updated research strategy by China to increase the accessibility of the research findings from the universities and research institutes at the international level.

The co-authorship between affiliated countries is depicted in Fig. 6. It should be noted that the close position of two countries indicates a strong relationship, in addition to the line thickness connecting the two respective countries. A total of 48 countries consisted of 17 countries in Asia, 20 countries in Europe, 7 countries in America, 2 countries in Africa and 2 countries in Oceania. The Netherlands was found to be the most affiliated country collaborating with 25 other countries; the strongest collaboration was with Brazil (11 publications), followed by Germany, Portugal, China, *etc*. Although the Netherlands were mostly collaborated with European countries, it has also created new collaboration with others such as Israel and Costa Rica, whereby each country was connected through 1 publication.

Meanwhile, China has made connections with 15 other countries, such as United States, Taiwan, Singapore, Qatar, *etc*. The strongest collaboration was identified between China and the United States with 26 publications, followed by collaboration with Taiwan indicated by 20 shared publications. The 267 articles published by China were funded by the National Natural Science Foundation of China, which has pushed the number of publications and international collaboration in this country. China has also opened a new collaboration with Ghana. Canada closely followed as the third most productive countries in the field of AGS. It has a strong relationship with China, sharing up to 14 publications of research articles. Canada also has collaborated with other countries, such as Italy, Indonesia, Japan, Brazil and the Netherlands. The United States was found to be one of the top collaborated countries with total link of 15 relations with other countries. Nevertheless, some countries have no connection or relation with any other countries. These included Poland, Romania, Mexico, Hungary, Austria and Turkey. It is expected

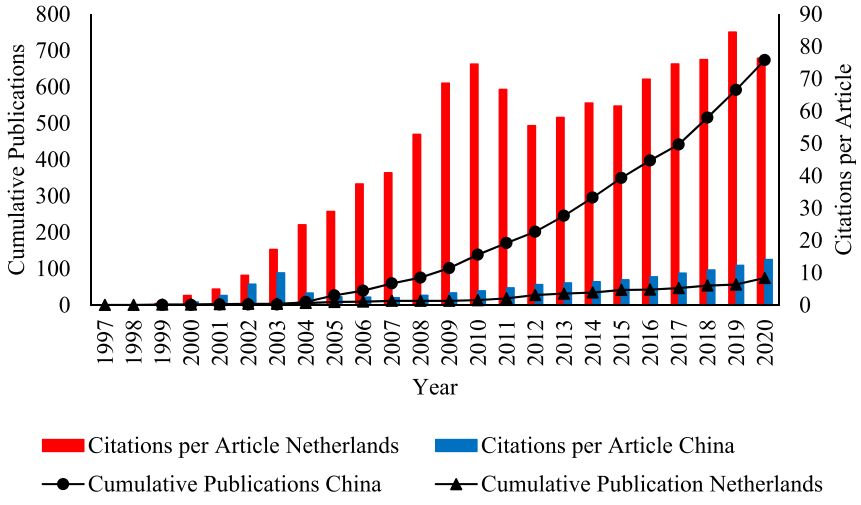

Fig. 5. Cumulative publications and citations per article between China and the Netherlands from 1997 to 2020.

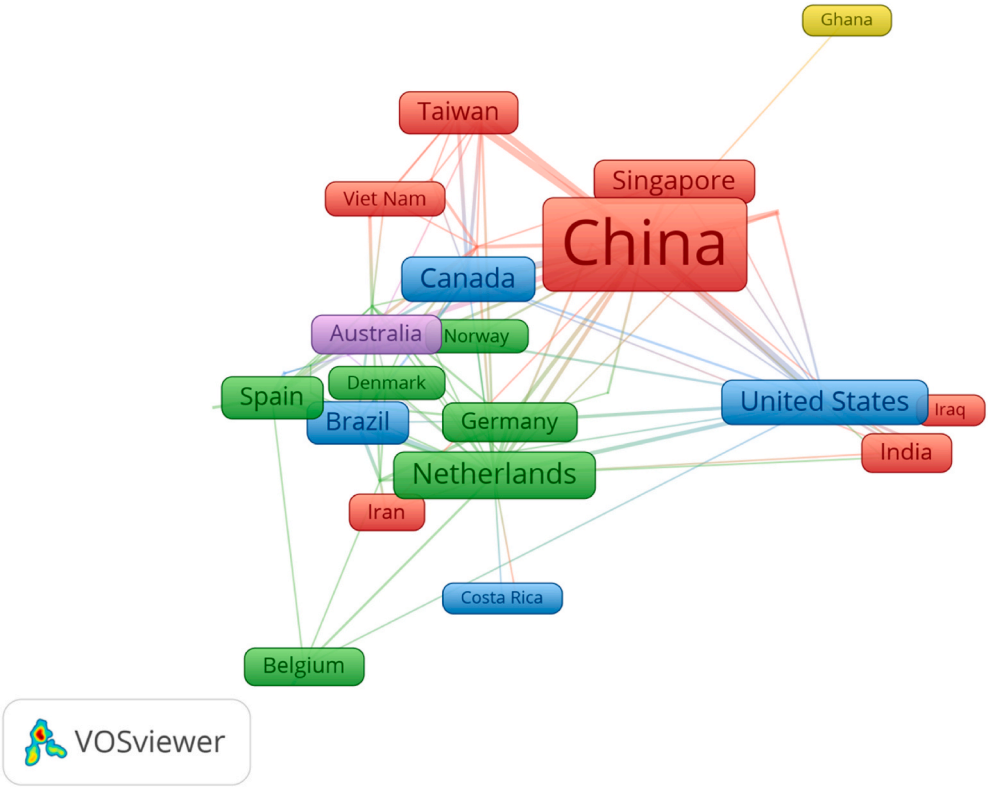

Fig. 6. A bibliometric map of countries co-authorship depicting the networks between 2 or more countries in publications of AGS (online map available at https://bit.ly/2WB8TXK).

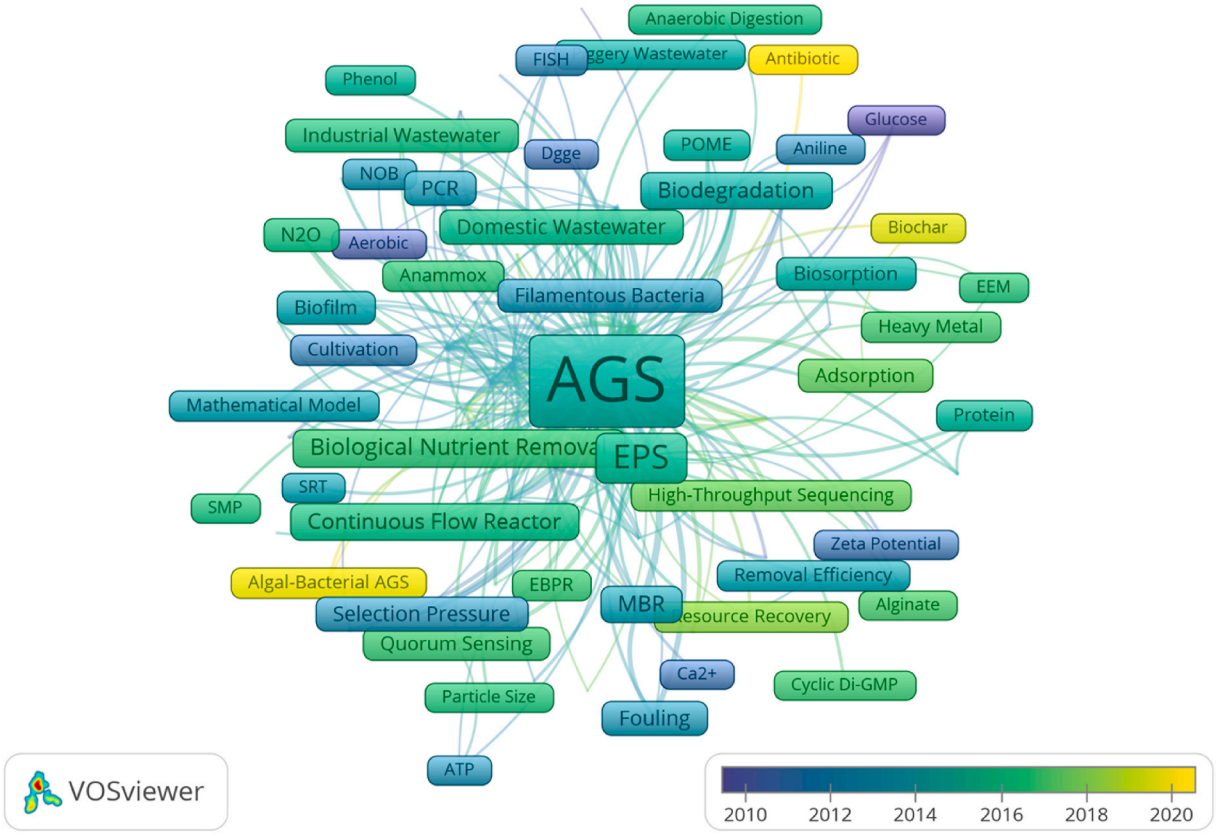

Fig. 7. The author keyword co-occurrences visualized based on the average publication year as shown in the legend (online map available at https://bit.ly/3nDeVkr).

that the finding of this study will aid in initiating new collaborations for these countries.

3.5. Distribution of author keywords

The 2207 author's keywords from the Scopus database were analyzed statistically using VOSviewer in order to visualize the research trend of AGS. However, many keywords are redundant. For example, some publications used the term "sequencing batch reactor," while others used the term "sequencing batch reactors," abbreviated as SBR. Therefore, similar author keywords were merged into one keyword. The final list consisted of 94 author keywords with minimum number of occurrences set to five. The minimum number of occurrences is important to ensure the depth and breadth of particular field of research. Fig. 7 demonstrated the co-occurrences relationship between the author keywords.

The highest occurrence was found for the keyword "AGS" with 895 times of occurrences, thus making it located at the center of the bibliometric map as shown in Fig. 7. The other popular keywords were "aerobic granulation" (234), "SBR" (203), "EPS" (167), "microbial community" (153) and "biological wastewater treatment" (120). These top keywords represent the key processes in AGS system, its application and the reactor operation (Adav et al., 2008).

The keyword "aerobic granulation" with average publication year 2013 represents the development or cultivation process of AGS (Liu and Tay, 2004). This keyword has been used in the most cited article and all first published articles in this field (Beun et al., 1999). The documents containing this keyword usually focused on the formation of aerobic granules during the wastewater treatment process. This keyword was linked with 57 other keywords, resulting in 252 total link strengths. Among related keywords are those regarding the affecting factors in aerobic granulation process, including "EPS", "OLR", "SBR", "temperature" and various types of wastewater (He et al., 2020c; Wan et al., 2018). The formation of aerobic granules is highly dependent on EPS production, whereby higher EPS production indicates a much higher rate of aerobic granulation (Purba et al., 2020; Sheng et al., 2010). In addition, it is also closely related to the keywords represent molecular mechanisms of aerobic granulation, including quorum sensing, microbial community, filamentous and heterotrophic bacteria, *etc.* (Lv et al., 2014). Besides, its close relation with various types of wastewaters, such as industrial (e.g., leachate, palm oil mill effluent (POME), saline wastewater, *etc.*), municipal and domestic wastewaters indicated that aerobic granulation process is feasible in different types of wastewaters (Abdullah et al., 2011; Alagha et al., 2020; Kim et al., 2016).

The second most popular keyword was "SBR" (average publication year 2013), occurred 203 times and related to 69 other keywords. This keyword was closely linked with the central theme of "AGS" and "aerobic granulation". Earlier publication in AGS have always been associated with SBR since the AGS process is typically conducted in SBR system (Beun et al., 1999; Morgenroth et al., 1997). It was demonstrated that 164 articles contained both "AGS" and "SBR" as the keywords, while 33 articles contained both "SBR" and "aerobic granulation". The modification on SBR operational parameters (e.g., "OLR", "aeration rate", "selection pressure", *etc.*) was reported as an interesting subject of research since it may directly affect the granulation process and treatment efficiency (Awang and Shaaban, 2016; Chen et al., 2018; Wang et al., 2018). Moreover, the link between SBR and numerous types of wastewaters indicated that this system is suitable to be used for a wide range of wastewater. The keyword SBR was also related with the keyword "pilot scale" (average publication year 2015) by 7 link strengths, demonstrated the application of SBR system in pilot-scale and full-scale treatment plant (Alagha et al., 2020; Pronk et al., 2015). Nevertheless, the other types of reactors (i.e., membrane bioreactor (MBR), sequencing batch airlift reactor (SBAR) and continuous flow reactor) have also emerged as alternative systems for AGS which targeted to improve of aerobic granulation process and wastewater treatment efficiencies (Corsino et al., 2016; Sajjad et al., 2016; Wang et al., 2018).

The next highly utilized keyword was "EPS" (average publication year 2015) which was closely related to the keyword of "aerobic granulation", "microbial community" and "quorum sensing", demonstrating that production of EPS is strongly influenced by the microbial composition and inter-cell communication (Sarma et al., 2017). Moreover, it was found to have links with "protein" and "polysaccharides", which are types of EPS in AGS (Deng et al., 2016). In addition, the relation between "EPS" and "alginate" has been recently highlighted. Potential resource recovery in the form of alginate may be achieved in AGS system, but this niche area still requires extensive studies to support the hypothesis (Lin et al., 2010).

Another focus of study in AGS is "microbial community" (average publication year 2016) which has occurred 154 times and linked with 60 other keywords, such as "PCR", "DGGE", "FISH", and a "high-throughput sequencing". High-throughput sequencing method was a relatively new process in microbial analyses compared to the other detection method. This was supported by the average publication year of "high throughput sequencing" which was in 2017 (Wang et al., 2016). Numerous keywords about groups of microorganisms were also linked with microbial community, including "anammox", "ammonia oxidizing bacteria (AOB)", "nitrite oxidizing bacteria (NOB)" and "heterotrophic bacteria". Several other keywords such as "OLR", "DO", "temperature", and "types of substrates" also exhibited close relations with this keyword, which representing the factors affecting the microbial community.

The keyword "biological wastewater treatment" (average publication year 2015) has been mentioned 120 times and was related with 49 other keywords. It has high correlation with "biological nitrogen removal", "biological phosphorus removal", "simultaneous nitrification and denitrification" and "simultaneous nitrogen and phosphorus removal". Previous studies have demonstrated the capability of AGS in performing nitrification and denitrification simultaneously due to the presence of aerobic and anoxic layer in the granules (He et al., 2020a). Moreover, simultaneous nitrogen and phosphorus removal was also possible because of the application of feast-famine regime in AGS system (Lochmatter et al., 2013). These applications have been studied for different types of wastewaters. In addition, the underlying mechanisms of the treatment processes were extensively studied by examining the microbial community of AGS, thus explaining the roles of a microbial group in the treatment process (J. Liu et al., 2017).

There were many other keywords in the field of AGS. Therefore, bibliometric analysis is useful to identify the past and current research progress in a specific field of research. Research novelty may be identified by creating a new link between 2 or more keywords. Keywords that are located far from each other in the map indicated less or no relations, thus will be interested in being investigated. It was argued that there were many unfolded fields in the AGS system that still require further experimental proof.

3.6. Research topics and pattern

AGS is an evolving field with high feasibility to be applied in wastewater treatment system (Liu and Tay, 2004). The past and current research trends have been outlined and discussed in detail. However, the bibliometric analyses of keyword co-occurrences may also be used to predict and derive the future research trend of certain fields. The analyses were performed by identifying author keywords with recent average publication year. Based on the analyses of keyword co-occurrences, the research trends of AGS can be divided into two main categories, namely technique processes and application.

3.6.1. Technique processes

Many keywords associated with affecting factors of the AGS process have been thoroughly elucidated in the previous studies. Operational

parameters in aerobic granulation, such as Ca^{2+} addition, carbon source, pH, OLR and aeration strategy, have been extensively studied since the beginning of its applications (Layer et al., 2020; Li et al., 2017; Long et al., 2015). Other technique processes, including anammox as well as anaerobic digestion and bioaugmentation coupled with AGS have also been elucidated (Winkler et al., 2012).

Nevertheless, the relatively long start-up period of AGS remains as the major drawback of AGS (Purba et al., 2021). Hence, the latest technique processes have been focusing on addressing this issue. This included but not limited to the recent utilization of biochar and microalgae in AGS, indicated by its average publication year of 2019. Biochar was first suggested to accelerate granulation by Zhang et al. (2017), whereby biochar from various sources such as palm frond, rice husk, walnut shell and petroleum waste were studied as the strategy to enhance the granulation process and to improve the granular stability (Wang et al., 2020). Harun et al. (2020) has reported the optimization of biochar dosage towards the granulation process, in which granulation started to appear as early as 14 days in the experimental period. Meanwhile, the other types of biochar (i.e., rice husk, rice bran and walnut shell biochars) were investigated for simultaneous aerobic granulation and treatment of petroleum wastewater (Ming et al., 2020). Reactor containing rice bran biochar exhibited most stable properties and treatment efficiency. Treatment of petroleum refinery wastewater using AGS mixed with petroleum waste biochar was also demonstrated and resulted in higher COD, oil and total nitrogen removal efficiencies (Wang et al., 2020). Nevertheless, the use of biochar in the AGS system is a new field prompting more investigations. The applications are currently still limited to synthetic and petroleum wastewaters, while the other types of wastewaters are still unknown. Moreover, the effect of biochar addition towards microbial composition in AGS needs to be extensively studied.

Improvement of granulation process may also achieved by integrating algae or microalgae into the system indicated by the keyword "algal-bacteria AGS" with average publication year of 2019 (L. Liu et al., 2017). Different strategies have been applied to induce algae growth in aerobic granules, such as by augmentation with specific algae species (e.g., *Scenedesmus* and *Chlorella*) or by utilizing indigenous algae species in the wastewater (Liu et al., 2018). The parameters affecting granulation process (e.g., light intensity or illumination strategy, salinity, aeration, etc.) were extensively studied (Meng et al., 2019a, 2019b; Zhao et al., 2018). Moreover, this system has been applied for treatment of synthetic saline, synthetic municipal and low-strength wastewater. However, majority of the applications are still focusing on treatment of synthetic wastewater while the treatments of actual wastewater using algal-bacteria granules are still limited. It is also worth noting that beneficial fatty acids have been detected in algal-bacteria granules that may be used for other applications, such as biodiesel production (Meng et al., 2019a, 2019b; Zhang et al., 2020). Despite its recent extensive investigation, many aspects have yet to be discovered in the application of algal-bacteria AGS (Lee and Lei, 2019).

3.6.2. Applications of AGS

The applications of AGS were majorly focusing on wastewater treatment efficiency, starting from the treatment of synthetic, municipal, domestic and industrial wastewaters. In terms of synthetic wastewater, various types of carbon sources have been utilized, such as glucose, acetate, butyrate, valerate and many more (Cai et al., 2019). At the later stage, AGS was reported to have the ability for simultaneous nitrogen and phosphorus removals, which was possible due to the unique structure of the granular sludge (He et al., 2020c). Therefore, the wastewater treatment applications were further investigated for treatment of actual municipal and domestic wastewaters, as well as for different types of industrial wastewater, including POME, dairy wastewater, poultry wastewater and swine wastewaters (Abdullah et al., 2011; Arrojo et al., 2004; Wang et al., 2019). In addition, the implementations of AGS system in full-scale treatment plants have demonstrated the capability of this system to be upscaled and commercialized (Pronk et al., 2015; Świątczak and Cydzik-Kwiatkowska, 2018). The vast applications of AGS are recently concentrating on the treatment of emerging micropollutants and viable resource recovery as the added value of wastewater treatment process. Thus, the following discussions are focusing on the research trend of AGS in above application.

The application of AGS for treatment of antibiotic containing wastewater (e.g., ampicillin, kanamycin, tetracycline, sulfamethoxazole, etc.) has gained significant attention with average publication year of 2019 (He et al., 2020; Kent and Tay, 2019; Xiong et al., 2020). The available literatures include the optimization of operating parameters (i.e., pH, initial antibiotic concentration and C/N ratio) (Kang et al., 2018; Yu et al., 2020) and the thermodynamic and kinetics of antibiotic degradation (Mihciokur and Oguz, 2016). The isolation of antibiotic degrading species such as *Pandoraea* sp. along with investigation of antibiotic resistant genes using a high-throughput sequencing method were also elucidated (Li et al., 2020). However, these studies are still limited to the treatment of synthetic and piggery wastewaters which typically contain high antibiotic concentration. Investigation on the treatment of hospital and pharmaceutical industry wastewaters will be useful to expand the knowledge in this niche area. The biodegradation product of antibiotic must be further explored to ensure no harmful by-products is released into the environment.

Wastewater and sludge from treatment processes are now seen as valuable sources containing various beneficial compounds, thus AGS system has now shifted towards resource recovery stage to promote more sustainable wastewater treatment system (Healy et al., 2015; Karakas et al., 2020). Thus, the keyword "resource recovery" exhibited considerably recent average publication year of 2018 in the bibliometric map. Among resources that have been recovered from granular sludge were alginate or alginate-like exopolymers (ALE), phosphorus and polyhydroxyalkanoate (PHA) (Kehrein et al., 2020; Luiz de Sousa Rollemberg et al., 2020). The physicochemical properties of these resources have been thoroughly elucidated by Schambeck et al. (2020). In addition, biolipids from algal-bacterial granular sludge have gained attention as the biolipids can be further utilized in many applications (Lee and Lei, 2019). Nevertheless, the resource recovery process needs to be investigated during the actual treatment process using AGS. Investigation of this matter in full-scale AGS treatment plants may be useful in future. Moreover, there is still lack of study in terms of the economic analyses throughout the process of resource recovery from the AGS system. These analyses may be used to move forward into commercialization of the recovered resources. This study suggests that there are many more applications of AGS prompting for more investigation by academic and industrial players in the future.

3.7. Limitations of study

This study has presented the quantitative analyses on research trends of AGS. However, the collected data were limited to the keyword of "aerobic granular sludge" OR "aerobic granul* sludge" OR "aerobic granulation" used in the titles, abstracts and author keywords. Thus, articles that do not contain these keywords was not included in the data. In addition, this study focused on articles in the Scopus database. Therefore, comparison of data outputs from other databases may be useful for a more comprehensive study. Moreover, analyses of different types of articles, including conference proceeding, book chapter and review articles may be considered in future.

4. Conclusion

This bibliometric study has provided an overview and detailed insight on past, current and future research trends in AGS using articles collected from the Scopus database. A total of 1203 research articles from 1997 to 2020 were analyzed using VOSviewer. It was discovered

that the publication number follows a power trendline of $y = 0.1979 \times ^{2.6688}$, indicating the rapid development in the field of AGS. The leading authors, countries, and institute were discussed, showing the dominance of China and the Netherlands, accounting for 62% of the total publications. It was suggested that the innovation of AGS would be focusing on the technique process and the applications of the system. For instance, the technical process may be focusing on study to enhance the granulation process and shorten the start-up period by utilizing biochar and integrating algae into the system. In addition, the application of AGS will be shifted towards performance in treating emerging micropollutants (e.g., antibiotics) while simultaneously achieving energy efficient system and reducing the sludge wastages by implementing resource recovery processes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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