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Current status and future prospects of simultaneous nitrification and denitrification in wastewater treatment: A bibliometric review

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ABSTRACT

A total of 516 documents were identified by using the suitable search strings in Scopus database and it showed that the annual publications related to simultaneous nitrification and denitrification (SND) in wastewater treatment increased steadily between the years 1985 and 2021. Through countries co-authorship analysis, it can be observed that China and Ministry of Education China were the most productive country and institution, respectively. The keywords analysis also revealed that there are still limited studies of SND in treating various types of wastewaters, including piggery wastewater and others. In addition, literature review regarding the functional microorganisms presents in the SND system and the factors influencing the SND performances were provided in this study. Extensive studies should be conducted in future to investigate suitable technologies and optimum operational conditions for different types of wastewaters to promote the development of SND in wastewater treatment.

1. Introduction

In the past few years, nitrogenous compounds are becoming more prevalent in natural water bodies, owing to the contamination from extensive industrial, agricultural, or urban activities, which are creating serious environmental issues. Excessive levels of nitrogenous contaminants in the raw water result in eutrophication, which can eventually damage the aesthetic and content of water quality and toxicity due to high levels of nitrite and the presence of harmful bacteria and microorganisms. It has become a critical concern in recent decades due to the excessive nitrogen discharge into the natural water bodies which cause algae to bloom and harm the aquatic organisms due to the bio-toxicity attributes of nitrogenous pollutants (Lei et al., 2019). As a result, the need for removing nitrogen from wastewaters has gained significant attention in order to relieve pressure on water resources and reduce polluted wastewater discharge into the natural environment (Amran et al., 2022; Bahrodin et al., 2022; Loh et al., 2022a; Syamimi Zaidi et al., 202). Conventionally, separate nitrification and denitrification processes are typically applied in the municipal wastewater treatment facilities in order to eliminate nitrogenous compounds from the wastewater. The nitrification process is performed by ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB) that convert ammonia into nitrate, whereas denitrification process is performed by heterotrophic denitrifying bacteria which denitrify nitrate into dinitrogen gas under anoxic conditions (Iannacone et al., 2020). Since the appropriate dissolved oxygen (DO) concentrations differ for nitrification and denitrification, conventional reactors typically employ one of the two solutions, which either dividing the reactors into separate aerobic and anoxic sections, or utilize intermittent aeration to vary the DO concentrations at each stage. However, these conventional biological nitrogen removal systems have obvious disadvantages, including high construction and operating costs, larger footprint, and complicated processes (Chang et al., 2019). Therefore, in the past few years, the simultaneous nitrification and denitrification (SND) process had been extensively utilized in the treatment of wastewater due to its ability to eliminate the requirement of an additional anoxic reactor when it is designed and optimized properly.

There are a few well-known SND mechanisms such as coexistence of

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common autotrophic nitrifying and heterotrophic denitrifying microorganisms in the biofilm owing to the DO concentration gradient while another mechanism refers to the coexistence of heterotrophic nitrifiers and aerobic denitrifiers in a single reactor under aerobic conditions (Chang et al., 2019). According to Bhattacharya and Mazumder (2021) findings, the development of oxygen gradient within the biofilm is crucial in creating distinct oxic zone and anoxic zone within the biofilm, which facilitate nitrification and denitrification process respectively. The nitrifiers tend to inhabit at the outer layer of the biofilm, where there is a direct contact with the oxygen while denitrifier reside in the anoxic zone where oxygen penetration is limited owing to the biofilm thickness. The oxygen gradient results in stratification of microbial communities with diverse functions which favour the SND process and ensure complete elimination of nitrogenous pollutants. In contrast, as a distinct nitrogen removal and SND mechanism, heterotrophic nitrification and aerobic denitrification (HNAD) attracted researchers' interest in recent years (Yan et al., 2022). HNAD microorganisms is a type of microbe capable of oxidizing ammonium nitrogen and performing denitrification even under aerobic conditions. This type of microbe has been found in a variety of environmental conditions and capable of performing both nitrification and denitrification at the same time under aerobic conditions. Moreover, HNAD microbes develop rapidly and promotes effective nitrification and denitrification capacities when given enough organic carbon sources (Song et al., 2021).

Despite an apparent increase of interest in wastewater treatment through SND, the bibliometric studies are still limited. To the best of our knowledge, there have been no studies that conducted bibliometric analysis of SND in the treatment of wastewater using Scopus database. Many databases such as Scopus, Web of Science and Google Scholar have reported on wastewater treatment using SND in the form of conference proceedings, book chapters, review and research papers. The massive volume of information in the field could be intimidating and thus, causing it challenging to determine the current research trends. Consequently, bibliometric analysis can be used to statistically analyse the available sources in the database in order to determine the future research trends (Purba et al., 2022). According to Gusenbauer and Haddaway (2020), Google Scholar is not suitable as the primary search engine for systematic searches as the search precision is significantly lower than 1 %. Moreover, in comparison to Web-of-Science that generally is not indexed majority of research papers in the field, Scopus provides detailed coverage and access to millions of scholarly articles (Loh et al., 2022b; Nabgan et al., 2022). Thus, using Scopus as a data mining source for SND in wastewater treatment could be a remarkable attempt in determining the global research focus and future prospects in this specific area.

The objective of this paper is to identify and discuss the global research focus and the future prospects of SND in wastewater treatment based on bibliometric approach, addressing the functional microorganisms that potentially present in the SND system and identify the factors influencing the SND performances.

2. Methodology

2.1. Bibliometric data collection

The bibliometric data collection that focuses on simultaneous nitrification and denitrification of wastewater was conducted from 16th June 2022 until 26th June 2022 using the search queries presented in Table 1. The terms such as ("simultaneous nitrification and de*nitrification" OR "simultaneous nitrification-de*nitrification" AND "waste*-water") were used to capture the data from SCOPUS database in the period between 1985 and 2021. The initial search query applied in this study was TITLE-ABS ("simultaneous nitrification and de*nitrification" OR "simultaneous nitrification-de*nitrification" AND "waste*water") AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (EXCLUDE (PUBYEAR, 2022)) which resulted in 523 documents.

Table 1
The search queriers used for each phase.

Remarks	Search query
General Search	TITLE-ABS (("biofilt*")) ("simultaneous nitrification and de*nitrification" OR "simultaneous nitrification-de*nitrification")
Narrowing	TITLE-ABS ("simultaneous nitrification and de*nitrification" OR "simultaneous nitrification-de*nitrification" AND "waste*water") AND (EXCLUDE (PUBYEAR, 2022)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j"))
Potential Review Articles	TITLE-ABS ("simultaneous nitrification and de*nitrification" OR "simultaneous nitrification-de*nitrification" AND "waste*water") AND (TITLE ("recent" OR progress OR review OR critical OR revisit OR advance* OR highlight OR perspective OR prospect OR trends OR bibliometric OR scientometric OR insights OR overview OR "state of the art" OR challenges OR updates) OR ABS (progress OR review OR bibliometric OR scientometric)) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (EXCLUDE (PUBYEAR, 2022))
EID review articles	(2-s2.0-85127341686) OR (2-s2.0-85073823596) OR (2-s2.0-77956885576) OR (2-s2.0-54549099293) OR (2-s2.0-34248650946) OR (2-s2.0-33748461064) OR (2-s2.0-33646737171)
Final	TITLE-ABS ("simultaneous nitrification and de*nitrification" OR "simultaneous nitrification-de*nitrification" AND "waste*water") AND NOT EID ((2-s2.0-85127341686) OR (2-s2.0-85073823596) OR (2-s2.0-77956885576) OR (2-s2.0-54549099293) OR (2-s2.0-34248650946) OR (2-s2.0-33748461064) OR (2-s2.0-33646737171)) AND (EXCLUDE (PUBYEAR, 2022)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j"))

The search was conducted using the "Title and Abstract", option available on the advanced search form of the database.

The initial search query only focused on journal articles and excluded the publication year of 2022. In order to identify the remaining review articles and eliminate it from the searching, additional phrases and terms (review, progress, recent, critical, revisit, advance, and highlight) were added in the initial search query (Loh et al., 2022b; Md Khudzari et al., 2018). Based on their EID, 16 potential review articles were identified and evaluated. The EID of the 16 review articles were included in the final search query in order to exclude it in the final search results. After removing the 7 review papers, the final search query yielded 516 documents. The procedure of identifying the suitable search queries is summarized in Fig. 1. Then, the final search results were assessed regarding the annual publication trends, the leading countries and institutions, as well as the popular authors keywords. The top 10 leading countries and institutions for SND in wastewater treatment publications were also visualized using Google My Maps. Furthermore, information for a country's total publications (TPC) and institution's total publications (TPI) were gathered and ranked according to their publication count, whereas information for single-country publications (SPC) were also taken into consideration by filtering out papers with affiliations to other countries and only focusing on papers with affiliations to the selected countries.

2.2. Analysis of bibliometric mapping based on countries co-authorship and keyword co-occurrence

The bibliographic data of the 516 documents obtained from the final Scopus search were used to create a bibliometric map using VOSviewer (version 1.6.16, Centre for Science and Technology Studies, Leiden University, The Netherlands). This included extracting citation and bibliographic information, abstracts, and author keywords.

For analysis of countries co-authorship, a thesaurus file was uploaded to VOSviewer along with the csv file for renaming (i.e. université de toulouse to france, harvard university to united states) and removing any unrelated countries or affiliations, including coordinación,

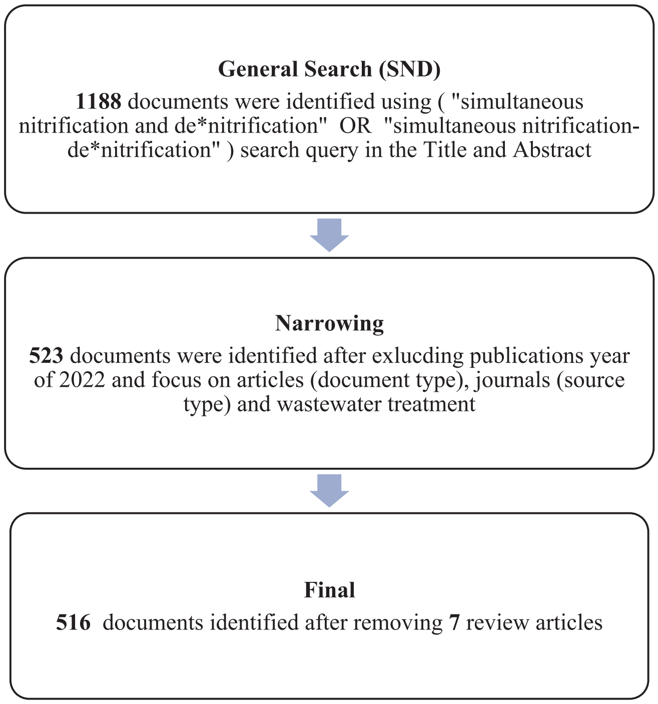

Fig. 1. Flow chart of bibliometric data mining for research articles in SND.

industrial, wastewater treatment laboratory, and west ger from the bibliometric map. In addition, the affiliated countries or institutions were regrouped into different continents such as Asia, Europe, America, Africa and Oceania.

Similar to countries co-authorship analysis, for the keyword co-occurrence analysis, additional thesaurus file was included in order to regrouped and relabelled some similar or synonym terms such as DO, dissolved oxygen (DO) and dissolved oxygen to DO. A total of 90 keywords were identified by setting the minimum threshold number of keywords occurrences at 3. In addition, based on the keyword analysis, a detailed literature review on the functional microbial community involved in the SND process, the factors affecting the SND performances (DO concentrations, C/N ratio, HRT, and pH), and the application of SND in treating different types of wastewaters, as well as the future research outlook were included.

3. Bibliometric analysis

3.1. Research trends based on the annual and cumulative publications

By focusing on SND in treatment of wastewater from 1985 to 2021, a total of 516 journal articles were retrieved. Fig. 2 visualizes the annual and cumulative publications of SND in wastewater treatment between years 1985 to 2021. It is noted that the publications of SND in wastewater treatment showed a progressive growth trend for 36 years. The consistent increase in the cumulative numbers of publications suggested that the annual publications trends is likely to continue increasing in the subsequent years. The first publication of SND in wastewater treatment started in 1985. However, SND in wastewater treatment did not receive much attention prior to 2005 as annual publications in each year were less than 10. Only 33 journal articles were published between 1985 and 2004, which accounted for approximately 6 % of the total cumulative publications from 1985 to 2021.

The strong interest of SND in wastewater treatment began in 2005, with a remarkable growth in the total publications' numbers from that year onward. The sharp increase in the publications numbers since 2004 is noteworthy, as the number of annual publications has progressively increased from 5 in 2004 to 46 in 2021, which represent a very significant 900 % growth. Furthermore, the number of published articles had exceeded 30 each year since 2014, indicating that the SND process in wastewater treatment started to receive significant recognition worldwide. The main reason SND process is receiving increasing attention throughout the past 15 years is largely attributed to its remarkable efficiency in treating different types of wastewater including domestic wastewater with low C/N ratio (Wu et al., 2021), high nitrogen and carbon saline wastewater (Wang et al., 2017) and leachate (Sun et al., 2017), adaptability to a wide range of dissolved oxygen (DO) and influent characteristics (Pan et al., 2022), and also able to reduce sludge production and carbon demand by over 30 % (Iannacone et al., 2019).

3.2. Countries and institution analysis

The leading countries and institutions in terms of numbers of publications are presented in Table 2 and visualized using google my map in Fig. 3. The publications were categorized in terms of total publication by countries (TPC), single country publications (SPC) and total publication by institutions (TPI). Based on the summarized results, six Asian countries, three American countries and one Oceanic country were ranked in the top 10 leading countries for SND in wastewater treatment. China was the frontrunner with 329 total publications, followed by Australia (37)

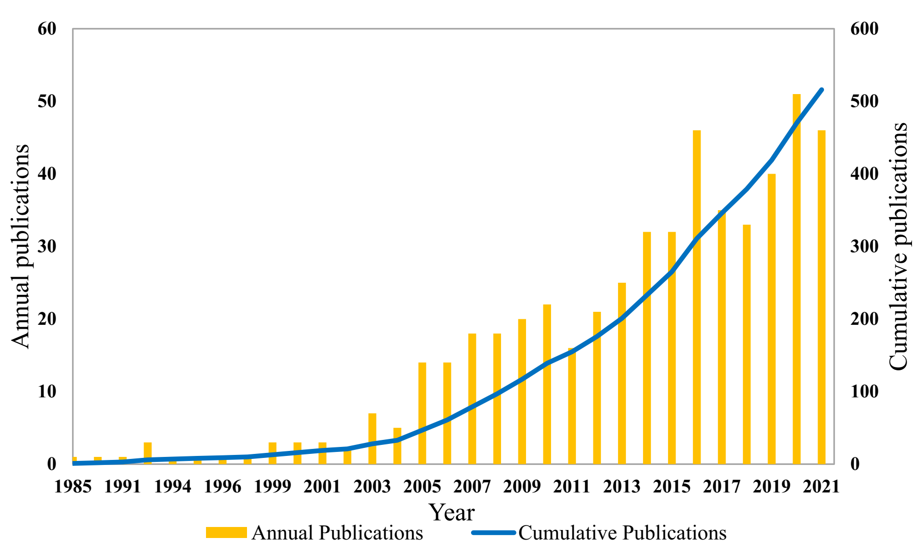

Fig. 2. Publications trends on SND in wastewater treatment from 1985 to 2021.

Table 2
Top 10 leading countries and institutions for SND research in wastewater treatment.

Rank	Country	TPC[a]	SPC[a] (%)	Institutions	TPI[a]
1	China	329	285 (86.7 %)	Ministry of Education China	64
2	Australia	37	11 (29.7 %)	University of Technology Sydney	12
3	United States	26	11(42.3 %)	University of South Florida, Tampa	3
4	Japan	25	11 (44.0 %)	Waseda University	3
5	Canada	21	11(52.4 %)	Western University	9
6	Iran	12	10 (83.3 %)	Razi University	5
7	South Korea	12	4 (33.3 %)	Pusan National University	2
8	Taiwan	12	5 (41.7 %)	National Taiwan University	4
9	India	11	10 (90.9 %)	Central Leather Research Institute India	3
10	Brazil	9	8 (88.9 %)	Universidade de São Paulo	4

[a] TPC – total publications by the countries; SPC –single-country publications; TPI– total publications by institutions.

and United States (26). Furthermore, Ministry of Education China was shown as the leading institutions with highest numbers of publications (64) while Pusan National University ranked at the lowest with 2 publications compared to the other top 10 institutions.

Additionally, among the top 10 countries, India recorded the highest percentage of SPC (90.9 %), followed by Brazil (88.9 %) and China (86.7 %). These group of countries prefer to focus their research on domestic sphere. Australia, on the other hand, had the lowest SPC (29.7 %), where 26 out of 37 of the total publications were affiliated up to 11 countries such as China, Taiwan, Vietnam, Japan, Thailand, Bangladesh, New Zealand, Singapore, Pakistan, South Korea and Saudi Arabia. This indicates the strong international collaboration between researchers from Australia and the other countries. The SPC percentage actually reflects the collaboration strength of each country. The higher the SPC percentages, the stronger the intra-country collaboration while the lower the SPC percentages, the stronger the inter-countries collaboration. Md Khudzari et al. (2018) highlighted international collaboration has numerous benefits beyond just expanding networks, exchanging and sharing information and expertise. It is also an effective way to achieve higher publication rankings.

Fig. 4 generated by the VOSviewer software visualizes the bibliometric mapping of co-authorship by countries in network visualization mode. This bibliometric mapping demonstrates the significance and present developments in countries research collaborations. According to Cavalcante et al. (2021), the lines linking the countries nodes in the bibliometric map reflect the co-authorship between the countries while the strength of the countries co-authorship were indicated by the distance between each clusters. Besides, the node size symbolises the publications numbers in the country, while the line thickness indicates the strength of the linkages which depends on the number of collaborations between the two countries (López-Serrano et al., 2020). China, Australia and United States contributed the most research output which was indicated by the network's three largest nodes. It can be observed that China had extensive collaborations with Australia and United States with the highest link strength of 14 and 7 between these two countries. Moreover, researchers from China also have strong collaborations with researchers from European countries such as France, Ireland, Belgium, Czech Republic, and Germany. Such extensive collaborations and high productivity of China may be attributed to the government's massive support in terms of research funding for wastewater treatment technology development. Furthermore, with regard to the faster urbanisation, greater environmental consciousness and stringent regulatory standards in China, numerous industries and researchers have started to explore efficient and novel wastewater treatment solutions (Ismail et al., 2021; Marcal et al., 2021). Moreover, 11 countries such as Austria, Iraq, Italy, Jordan, Malaysia, Poland, Romania, Russian Federations,

Fig. 3. Geographical mapping of leading countries and institutions.

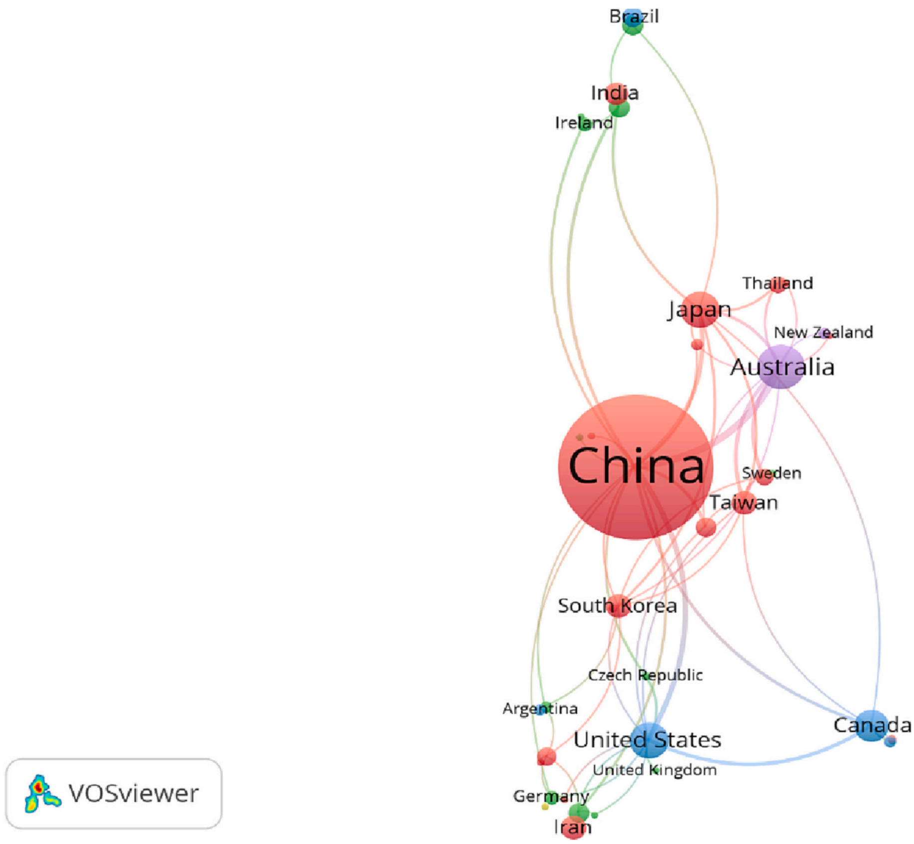

Fig. 4. Bibliometric mapping of co-authorship by countries.

Slovakia, South Africa and Switzerland do not have any international collaborations in the publications related to SND in wastewater treatment. This could explain the lower average citations number received by these countries compared to countries with stronger international collaborations.

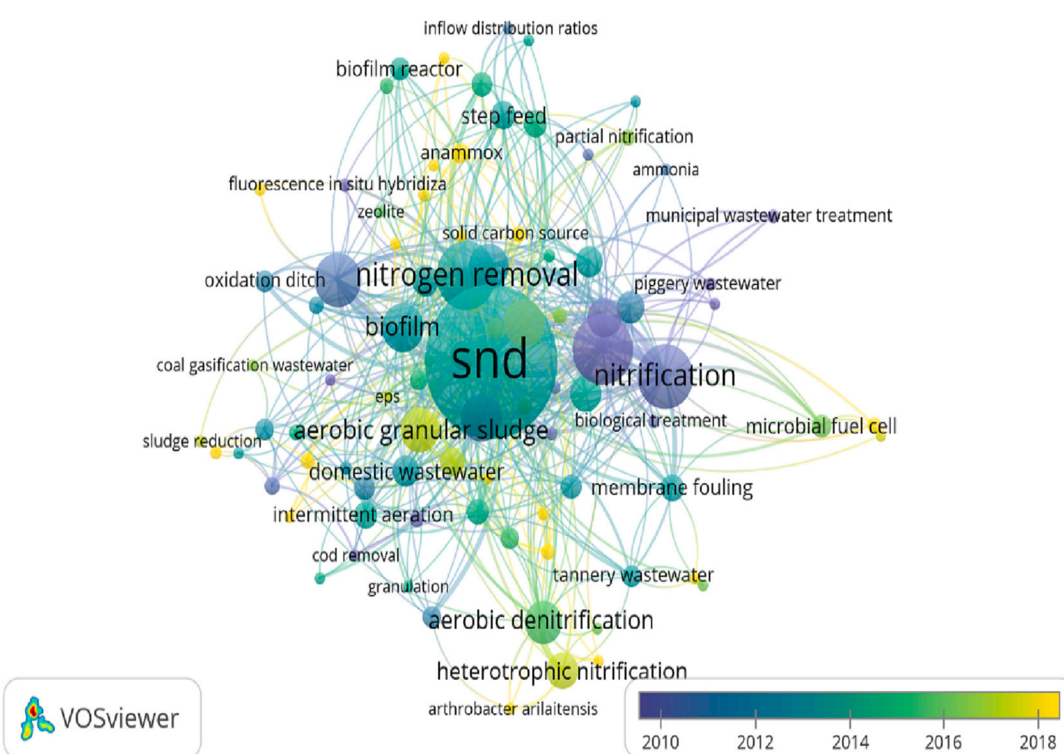

Fig. 5. Bibliometric mapping of co-occurrence by authors keywords.

3.3. Keyword analysis

Author keywords are words or phrases that characterise a publication's field or research topic. In order to attract researchers that are interested in the particular research fields and to boost the citation scores, the authors must include relevant keywords in their keyword list (Ismail et al., 2021). In this study, the research focus of SND in wastewater treatment was identified through a co-occurrence keyword analysis conducted using Vosviewer. There were a total of 1260 keywords identified and 90 keywords meet the threshold of at least 3 occurrences. Fig. 5 shows the bibliometric mapping of co-occurrence by authors keywords in overlay visualization mode.

As expected, the term "SND" which located at the centre of the bibliometric map outshined other authors keywords with 209 occurrences, 74 links and 332 total link strengths, followed by the terms "denitrification" (57 occurrences), "nitrogen removal" (55 occurrences) and nitrification (50 occurrences). The authors keyword "SND" had a strong link strength with these keywords as these keywords represent the key processes and mechanism involved in SND. Autotrophic nitrification and heterotrophic denitrification are conventional nitrogen removal processes commonly utilized in wastewater treatment due to their efficiency and affordability (Luo et al., 2022). Besides, the author keyword, "biofilm", with average publication of 31 occurrences was also one of the popular keywords. This can be explained by the potential of the biofilm technologies in promoting the SND performances. According to Liu et al. (2021) and Iannacone et al. (2019), oxygen gradient established in the biofilm due to the oxygen diffusion limitation facilitates the formation of distinct aerobic, anoxic, and anaerobic layers, where the denitrification process happens in the deeper anoxic and anaerobic layers of the biofilm while the nitrifying microorganisms exist on the aerobic surface. This microbial stratification ensures the feasibility of the SND process. Compared to activated sludge system such as oxidation pond and sequencing batch reactor, biofilm technology clearly appears to be a more promising option for SND process due to the oxygen gradient along the biofilm that promotes microbial stratifications, require lesser space and have a simple solid-liquid separation process (Liu et al., 2021). Therefore, it can be observed that the author keyword "biofilm" outperformed the other keywords such as activated sludge, oxidation pond and sequencing batch reactor.

The correlation between SND process and the author keywords helps the researcher in determining the direction of global research focus and future research trends. Other than the keywords mentioned above, the top 10 terms, "microbial community", also received noticeable attentions from the researchers. This particular keyword had a total of 47 link strengths as it was associated with 28 other keywords. Previous study by Wu et al. (2021) had shown that the microbial community structures in the SND process are closely linked to the environmental conditions and the quality of the treated effluent. Moreover, the treatment performance of a biological treatment system are often linked to the operational or structural factors that govern the functional microbial community (Zhang et al., 2020). Referring to the keywords such as DO (dissolved oxygen), C/N (carbon to nitrogen) ratio, HRT (hydraulic retention time), and pH, it can be noticed that these keywords represent the operational parameters that largely influence the SND performances in wastewater treatment. Among the 4 keywords ranked at the top 10 with 28 occurrences, followed by C/N ratio (7), HRT (6), and pH (4). This ranking indicates that DO is the main operational factor that plays a significant role in regulating the SND performances. The average publication years of these 4 keywords were higher than 2012, which indicates the high popularity of these keywords in recent decades. It can be noticed that there are increasing numbers of researchers investigating the optimum operational factors for the SND process recently (Chang et al., 2019; Wang et al., 2020; Wu et al., 2021) and the occurrences of the keyword "process optimization" also supported this statement.

4. Microbial community that are involve in the SND process

Table 3 summarizes the classification of functional microorganisms in genus level that are commonly involved in the SND process. According to Duan et al. (2021), the conventional biological nitrogen removal process consists of the oxidation of ammonia to nitrite and nitrate through aerobic autotrophic nitrifying microorganisms under oxic conditions, followed by denitrification by heterotrophic denitrifying microorganisms under anoxic conditions. Ammonia oxidizing bacteria (AOB) are part of the autotrophic nitrifiers which are responsible for converting ammonia to nitrite, while nitrite oxidizing bacteria (NOB) convert nitrite to nitrate. AOB can be divided into two monophyletic groups: β-proteobacteria, which contains *Nitrosomonas* and *Nitrosospira*, and γ *-proteobacteria*, which includes *Nitrococcus*. Besides, *Nitrobacter* and *Nitrospira* are the common genera of nitrite-oxidizing bacteria (Bhattacharya and Mazumder, 2021; Yan et al., 2019). Chang et al. (2019) supported the statement by reporting the dominant nitrifying bacteria at genus level present in the SND biological folded non-aerated filter system were *Nitrosomonas*, *Nitrobacter* and *Nitrospira*. It can be observed from the study that the SND biological folded non-aerated filter system achieved remarkable nitrification performance with the abundance of these functional nitrifying microorganisms. For denitrification process, the majority of denitrification processes are dominated by heterotrophic denitrifying bacteria. These heterotrophic denitrifiers utilize nitrate as the electron acceptor in the electron transfer pathway under anaerobic or anoxic conditions (Si et al., 2018). It was reported by a few studies that the common heterotrophic/ anoxic denitrifiers genera present in the wastewater treatment were *Acidovorax*, *Thermomonas*, *Defluviimonas*, *Gemmobacter Thauera*, *Zoogloea* and *Azoarcus*. Chai et al. (2019) also mentioned the functional microorganisms in the SND reactor treating wastewater with low C/N ratio was dominated by *Zoogloea* and *Nitrospira* bacteria. *Zoogloea* is one of the most common denitrifying bacteria that poses similar denitrification properties as *Pseudomonas* which reduces NO_2 directly to N_2 while *Nitrospira* enhanced the nitrifying ability of the reactor without NO_2 accumulation. The co-existence of diverse types of functional bacteria ensures the feasibility of the SND process.

Recently, the roles and presence of HNAD bacteria in SND wastewater treatment system received noticeable attentions from several researchers. According to Huang et al. (2020), HNAD bacteria have a variety of nitrogen metabolic pathways that directly utilize different

Table 3
Classification of functional microorganisms present in the SND process at genus level.

Functional types	Genus	References
Autotrophic nitrifiers (AOB)	- *Nitrosomonas* - *Nitrosospira* - *Nitrococcus*	(Bhattacharya and Mazumder, 2021; Yan et al., 2019)
Autotrophic nitrifiers (NOB)	- *Nitrobacter* - *Nitrospira*	(Chang et al., 2019)
Heterotrophic/Anoxic Denitrifiers	- *Acidovorax* - *Thermomonas* - *Defluviimonas* - *Gemmobacter* - *Thauera* - *Azoarcus* - *Zoogloea*	(Liu et al., 2021; Si et al., 2018; Yan et al., 2019; Zhang et al., 2018)
Heterotrophic nitrification and aerobic denitrification bacteria	- *Acinetobacter* - *Bacillus* - *Cupriavidus* - *Pseudomonas* - *Rhodococcus* - *Klebsiella* - *Arcobacter* - *Paracoccus* - *Rhodobacter* - *Flavobacterium*	(Chen et al., 2022; Huang et al., 2020; Liu et al., 2021; Yan et al., 2019)

carbon sources to convert inorganic nitrogen into gaseous or organic nitrogen under aerobic conditions via partial nitrification, dissimilation, assimilation or denitrification. Compared to conventional nitrifiers, HNAD bacteria have a faster growth rate, superior environmental flexibility, and the ability to remove nitrogen and COD simultaneously under aerobic conditions (Yao et al., 2013). Some of the common HNAD genera that were reported includes *Acinetobacter*, *Bacillus*, *Cupriavidus*, *Pseudomonas*, *Klebsiella*, *Rhodococcus* and *Arcobacter*. Chen et al. (2022) conducted a study by using rotating biological contactor inoculated with HNAD bacteria in treating livestock and poultry breeding wastewater. The microbial diversity analysis revealed that HNAD bacteria such as *Acinetobacter*, *Flavobacterium*, *Arcobacter* and *Pseudomonas* capable of converting nitrogenous compounds into nitrogen gas directly were present. With the abundance of these functional microorganisms, the treatment system was capable of recording a maximum removal efficiency of TN and NH_4-N at approximately 68.41 % and 99.6 %. Xie et al. (2021) also reported that bacteria strain of *Pseudomonas mendocina* X49 shows promising potential in achieving effective SND capabilities under heterotrophic aerobic conditions.

Although researchers throughout the world have investigated the microbial community in the SND system, the dominant functional microorganisms reported varies according to different studies. There are still incomplete understanding on the microbial community involved and present during the SND process. Therefore, future research in the microbial composition and their specific functions are needed as it provides a foundation for the nitrogen removal process in wastewater through SND.

5. Factors affecting SND performance

Based on the co-occurrence author keywords analysis, the main factors that influence the SND performances include DO concentrations, C/N ratio, HRT and pH. Success of SND process often requires unique and separate operating conditions which is hard to achieve. Based on a few experiments and research on SND, it can be observed that maintaining a minimal dissolved oxygen (DO) concentration that does not negatively affect the nitrification process enhanced SND, whereas the effect of C/N ratios showed opposite effect where a minimum threshold value needs to be ensured. The HRT of the system and pH of the influent should also be maintained within an appropriate range to maximize the functional microorganisms' activities.

5.1. Effect of dissolved oxygen concentrations on SND performance

The concentration of dissolved oxygen is among the critical factors that can influence the SND performances. Several investigations have shown that at low DO levels, the nitrate generated during the nitrification process in the aerobic zone may diffuse into the inner anoxic zone alongside substrates, allowing denitrification process to occur within the inner layers (Liu et al., 2010). Wang et al. (2020) conducted a study and found out that DO concentrations is a critical factor that influences the NH_4-N removal performance. The study showed that when the DO concentration was 1.5 mg/L, the removal efficiency of NH_4-N and TN was approximately 42.0 %, while when the DO concentration was increased to over 2.5 mg/L, NH_4-N removal was nearly complete, ranging from 93.0 % to 96.9 %.

In contrast, SND efficiencies and the TN removal rates decrease, while the nitrate accumulation increase when the DO concentrations increase from 2.5 to 5.5 mg/L. Low DO levels resulted in a lower nitrification rate and influences the total nitrogen removal while high DO concentrations may result in a lower denitrification rate by causing the shrinking of the anoxic zone. Denitrification is largely inhibited by high concentrations of DO in the reactor, whereas incomplete nitrification is caused by low DO concentrations (Bhattacharya and Mazumder, 2021). Although Hasan et al. (2009) claimed that a minimum DO value of 2–3 mg/L is required for complete nitrification, another study by Liu et al. (2021) reported that a DO value of 0.75 ± 0.25 mg/L or higher appears to be sufficient for nitrification in the MBBR. It was observed that the NH_4-N, COD and TN removal efficiencies of 88.6 %, 90.5 % and 76.6 % were achieved at low DO concentrations of 0.75 ± 0.25 mg/L. Furthermore, Liu et al. (2010) also supported the statement by stating that DO concentrations of 1.0–1.2 mg/L is sufficient for nitrification process in domestic wastewater treatment using oxidation pond. Therefore, these findings indicate that maintaining a low DO range is sufficient to ensure successful nitrification and denitrification performance in SND process. Another advantages of performing SND in DO levels as low as 1 mg/L would significantly lower the plant's aeration costs and CO_2 emissions (Iannacone et al., 2019).

5.2. Effect of C/N ratios on SND performance

C/N ratio of the wastewater is another crucial factor in ensuring the feasibility of the SND process, as it serves as substrates that support the development of functional microorganisms in the biological system. However, if the C/N ratio in wastewater treatment process is too high, the accumulation of heterotrophic microorganisms may shock the autotrophic microorganisms which lead to reduction in nitrification efficiency. Conversely, the absence of sufficient organics will reduce the denitrification efficiency (Chang et al., 2019). Therefore, maintaining a suitable range of C/N ratio is important in maintaining the SND performance.

A few studies have shown that achieving SND with low C/N ratios without an external carbon sources were difficult, and most effective SND process were observed at high C/N ratios of 9, 21, 13, 9 (Bueno et al., 2018; Fu et al., 2010; He et al., 2009). Bueno et al. (2018) investigated the biological nitrogen removal through SND in a continuous flow activated sludge system. The effluent ammonia, nitrite, and nitrate were found to be low when the C/N ratio was kept between 6.3 and 9.3. He et al. (2009) also mentioned that the concentration of TN and NH_3-N in the permeate increased when the C/N ratio decreased. This is mainly because high ammonia load would shock the biological system and thus, leading to incomplete nitrification process. Moreover, insufficient influent COD levels can also hinder biological denitrification, which cause an accumulation of NOx-N in the permeate.

Iannacone et al. (2019) reported C/N ratio greater than 4.2 can cause an overgrowth of heterotrophic aerobic bacteria and negatively impact the efficiency of both nitrification and denitrification. It was observed that biofilm development in the microaerobic moving bed biofilm reactor (mMBBR) at a feed C/N ratio of 2.7 lead to a stronger nitrification process than those reported at higher C/N ratio. Long-term SND in the mMBBR was not applicable with feed C/N ratio of 5.6. This statement is supported by the research of Matsumoto et al. (2007). According to the researcher's membrane-aerated biofilm reactor mathematical simulations, optimal SND occurred at C/N ratio of 3.75, with constraints stating that nitrogen removal would not surpass 30 % if the C/N ratio was less than 1 or larger than 7. Further studies regarding the optimum C/N ratio are needed as ideal C/N ratio reported for SND process in different bioreactors show a high degree of variability, which can be related to the differences in carrier materials, biofilm composition, types of influent, and treatment strategies.

5.3. Effect of HRT on SND performance

Hydraulic retention time (HRT) is another crucial operational factor in maintaining the long-term SND performance since it is directly associated with the substrates capacity that are to be processed per unit time and the efficient interaction between the substrate and the functional microorganisms (Loh et al., 2021). Study by Chang et al. (2019) stated that a very short HRT is not favourable for the effective contact between the biofilm and the biodegradation of contaminants, which result in insufficient microbial reactions. The residual organics present in the wastewater would also deteriorate the biological activity of nitrifiers, resulting in a detrimental impact on the removal of nitrogenous contaminants.

Wang et al. (2020) investigated the SND and nitrogen removal efficiency under four HRT conditions (6–12 h) while the DO, pH and C/N ratio were kept around 2.5 mg/L, 8.0, and 12 respectively. The study found the removal of NH_4–N and TN reached maximum at 97.5 % and 83 % when the HRT was 10 h. On the other hand, the denitrification performance was considerably inhibited and accompanied with high accumulation of NO_3–N when the HRT exceeded 10 h. This resulted in a significant drop in TN removal and SND efficiency. The extended hydraulic retention times largely influence the proliferation of nitrifiers, resulting in a greater consumption of COD and a weakening of the denitrification process. In contrast, Wu et al. (2021) observed a significant drop in the nitrogen removal performance of a lab-scale MBBR when the HRT was reduced from 13 h to 6 h while the effluent NO_3-N and CODcr increase when the HRT decreased from 6 to 3 h. The efficiency of nitrogen removal decreases with the decrease of HRT owing to the shorter effective contact time between the substrates and the functional microbes. Furthermore, the shorter HRT generates higher shear force and volume load, which makes the biofilms more likely to be washed away from the carriers, leading to a significant reduction in removal efficiencies. The poor denitrification performance was likely attribute to the higher flow rate that wash off the soluble organic carbon with the effluent, preventing it from being consumed by the denitrifiers (Wu et al., 2021; Zhang et al., 2019).

5.4. *Effect of pH on SND performance*

pH is a measure of the hydrogen ions concentrations, commonly known as the degree of acidity or alkalinity in a solution. pH has a significant impact on the growth and metabolism of microorganisms, as it alters the ionic characteristics of microbial cells and impacts the microbial growth (Srivastava et al., 2020). Wang et al. (2020) examined the impact of pH (6.5–8.5) on the SND efficiency and the TN and NH_4-N removal in a moving bed sequencing batch reactor. It was observed that the pH changes significantly affect the removal efficiency of the TN and NH_4-N. pH 6.5 was found detrimental to the NH_4-N and TN removal efficiency and the NH_4-N and TN removal efficiencies rise gradually when the pH increased from 7 to 8.5. Furthermore, study by Wang et al. (2005) also stated that the best removal efficiency of NH_3-N and TN by SND was reported to be in the pH range of 7.0–7.5, while nitrification efficiency is severely inhibited when the pH is higher than 9 and lower than 5. He et al. (2009) supported the statement that the removal of TN and NH_3-N was better at neutral condition (pH 7.2) compared to acidic (pH 4.8) and alkaline (pH 9.7) conditions. Based on all of these findings, it can be concluded that pH is not the most essential element in affecting the SND performance in a biological treatment system, but it serves as a vital condition that must be considered throughout the experiment to optimize the potential of the SND process.

6. Application of SND in treating different types of wastewaters

Fig. 6 illustrates various wastewater types and their respective occurrences which were retrieved from the list of keywords generated from the analysis of keyword co-occurrence in order to determine the current research focus of SND. From the figure, there were 8 types of wastewaters identified which include domestic wastewater, municipal wastewater, tannery wastewater, piggery wastewater, aquaculture wastewater, coal gasification wastewater, dairy wastewater and petrochemical wastewater. Out of the various types of wastewaters identified, domestic wastewater had the highest occurrences with 15 occurrences (28 %), followed by municipal wastewater (26 %) and tannery wastewater (15 %). This finding indicates that SND process is very effective in treating domestic wastewater. Study by Liu et al. (2020) supported the statement by reporting on the superior SND performance in treating real domestic wastewater. From the study, highly efficient SND performance was achieved with a maximum TN removal of 75.9 % and 71.8 % of SND efficiency. In contrast, the occurrences of the term's piggery wastewater (4), aquaculture wastewater (3), coal gasification wastewater (3), dairy wastewater (3) and petrochemical wastewater (3) were all less than 10

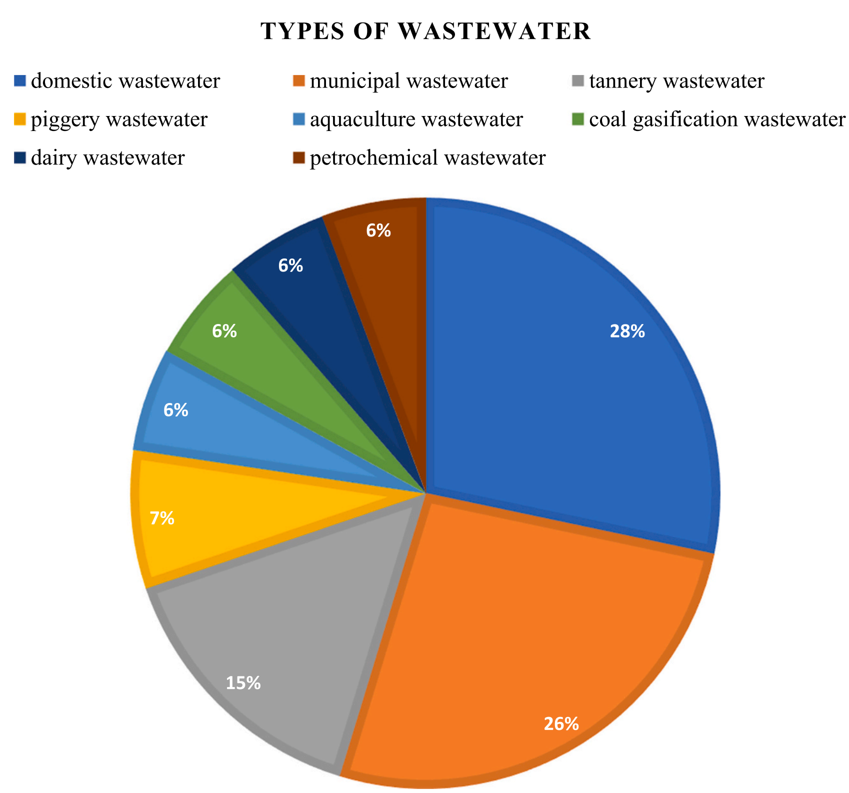

Fig. 6. Application of SND in treating different types of wastewaters.

%. Moreover, others types of wastewaters such as food industry wastewater, hospital wastewater and Palm Oil Mill Effluent (POME) have occurrences of less than 3. This observation indicates that there are still potential gap remaining in the research of SND process and further studies are needed to address the treatment of these types of wastewaters in the future.

7. Limitation and future outlook

The bibliometric review on the global research focus and future prospect of SND in wastewater treatment have been presented in this study. However, the terms "simultaneous nitrification and de*nitrification" OR "simultaneous nitrification-de*nitrification" used in the search strings of the titles and abstracts may limit the data obtained. As a result, potential articles that were related to SND, but do not contain these specified keywords in the title or abstract will be excluded from the searchers. These limitations may be resolved in the future when advanced technologies such as artificial intelligence and big data are applied in the bibliometric analysis.

Although SND shows promising potential in wastewater treatment, there are still significant research gap that are present in this area. Through countries co-authorship analysis, it can be noticed that there is still shortage of research regarding the SND wastewater treatment in the African countries and in Southeast Asian countries such as Malaysia and Indonesia. Moreover, through bibliometric mapping of the authors keywords, it can be observed that the current research trends of SND in wastewater treatment focus on using biofilm technologies in promoting SND, investigating the functional microorganism that are involved in the SND system, identifying the main factors influencing the SND performances (DO concentrations, C/N ratio, HRT and pH) and determining the optimum operational conditions to maximize the performance of SND. Additionally, despite the fact that developed countries in Europe and North America largely contributed to the research output of SND in wastewater treatment, most of the studies focus on domestic wastewater treatment, municipal wastewater treatment, and tannery wastewater treatment which are indicated by the high occurrences of these terms. Therefore, researchers are encouraged to expand their studies in the future by investigating on the suitable technologies and optimum operational conditions for different types of wastewaters which are less reported such as piggery wastewater, aquaculture wastewater, coal gasification wastewater, and dairy wastewater. Other than that, countries such as Malaysia could focus on the research of SND in the treatment of POME, as the studies regarding POME is still limited and POME is one of the major environmental pollutants in Malaysia.

8. Conclusion

SND is undeniably an efficient approach for the treatment of nitrogenous contaminants from wastewater. This review has highlighted the current research focus and the future prospects of SND in wastewater treatment through bibliometric approach, addressing the functional microorganisms that potentially present in the SND system and the factors influencing the SND performances. As for keyword analysis, the high occurrences of the keywords such as biofilm, microbial community, and the influencing factors including, DO concentrations, C/N ratio, HRT, and pH indicate that current global research of SND in wastewater treatment focus on using biofilm technologies and investigating the functional microorganism and operational factors that influence the SND performances. In addition, autotrophic nitrifying bacteria, heterotroph denitrifying bacteria, and heterotrophic nitrification and aerobic denitrification bacteria were the main functional microorganisms that contribute to the efficiency of the SND system. DO, C/N ratio, and HRT were the dominant factors that contribute to the efficiency of SND while pH is not the most essential element, but serves as a vital condition that had to be taken into account throughout the SND process. Lastly, considering the gaps that still exist in this field of investigation, extensive studies should be conducted in the future to investigate the feasibility of SND in treating various types of wastewaters.

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.

Data availability

Data will be made available on request.

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