Role of Ecological Floating Beds in Nutrients Removal from Polluted Surface Water: A Systematic Review and Bibliometric Analysis

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Abstract

An in-depth understanding of the remediation of polluted water via Ecological Floating Beds (EFBs) is essential, as they are a popular bioremediation technology. The present study intends to identify the existing knowledge on the application of EFBs for nutrient pollutants removal and to provide insights to enhance the efficiency of EFBs performance. By following Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) guidelines, 55 articles were retained after an automatic, manual screening and eligibility assessment. The selected articles were subjected to descriptive analysis and keyword co-occurrence analysis using Biblioshiny R and VOSviewer software to identify knowledge in terms of pollutant type, removal mechanism, and performance enhancement means. Accordingly, the key knowledge identified is (1) the main nutrient pollutants removed by EFBs are nitrogen and phosphorous, (2) the promising pathways of nutrient removal are microbial degradation and plant uptake, (3) Proteobacteria is the most abundant bacterial phyla that are involved in nitrogen removal via denitrification (4) the performance of EFBs can be enhanced with the addition of various materials, whereas Zeolite showed profound effects in nutrient removal. The knowledge identified in this study would serve as a source for scholars and many stakeholders who are interested in implementing EFBs for pollution remediation

Keywords: Ecological floating bed, Denitrification, Nitrogen, Phosphorous, Removal efficiency

I. INTRODUCTION

Mineral nutrients primarily nitrogen (N) and phosphorous (P) enter the surface water systems via various routes such as surface runoff that carries dissolved surplus agrochemicals (Huang et al., 2017), eroded soils and sediments from agricultural lands, discharge of secondary effluents and wastewater from wastewater treatment plants and industries (Sun et al., 2020; Sun et al., 2021a, b, Meng et al., 2021), disposal of animals' and birds excretes and feces etc. The resulted higher concentrations of these nutrients cause eutrophication (Beusen et al., 2016; Ahmed et al., 2017; Gao et al., 2017) and water quality deterioration, which is obviously visible with algal blooms, proliferation of aquatic flora and unpleasant odour and colour. Consequently, it results loss of ecological integrity, decreased aquatic biodiversity, disappearance of submerged vegetation, potential production of toxins (Moal et al., 2019) and may end up with the threatening of human health.

To address these adverse effects caused by eutrophication and subsequent pollution, it is necessary to remove the causal nutrients (N and P), which is carried out with many methods and techniques including physical (e.g. filtration, flotation, coagulation, sediment dredging, mechanical aeration) (Chen et al., 2018; Pereira et al., 2018), chemical (flocculation settling, chemical algal killing) (Wu et al., 2011) and ecological (macrophyte remediation, constructed wetland, floating bed) (Walaszek et al., 2018). The Ecological Floating Beds (EFBs), have received much attention and become popular for pollutants removal. This is because, it is a low cost, simple method for construction and maintenance (Li et al., 2018). Moreover, it requires no land and water depth (Gao et al., 2018) and beautifies the environment (Zhu et al., 2023). Meanwhile the other methods have many drawbacks including low efficiency, short duration, large investment, wide occupation of land (Li et al., 2015), low adaptability and stability (Yang et al., 2021) and pollution acceleration through resuspension (Chen et al., 2021).

Even though the EFBs are superior in pollution remediation, their performance is not stable and satisfactory always. In particular, limited biomass and growth of plants subjecting to seasonal changes affects the performance of EFB (Sun et al., 2009; Wang et al., 2018) and they are vulnerable to lower temperature (Cao et al., 2016). Furthermore, the constituents of water being treated are also influence the performance of EFBs. Notably, the higher concentrations of nutrients especially ammonium nitrogen (NH_4^+) (>10 mg/L) cause toxicity to plants, inhibit nitrifying and heterotrophic bacteria (Li et al., 2020), while lower organic carbon content affects the denitrification process. As a result, the traditional EFBs have been found inefficient for treating hyper eutrophic water (Yan, et al., 2021), secondary effluent and wastewater with low C/N ratio (Huang et al., 2020; Sun et al., 2020; Sun et al., 2021a, b). Thus, there is a necessity to improve the performance of EFBs, hence, the scholars have been trying with numerous approaches. In this context, addition of various materials including external carbon source (Huang et al., 2020), biofilm carriers (Yang et al., 2020; Hu e t al., 2020) and electron donors (Sun et al., 2021a, b) are notable approaches that have been found successful in strengthening of EFBs' performance. Specifically, addition of carbon source, prepared by mixing the reed straw powder and polycaprolactone, to the traditional EFB with *Iris wilsonii* increased the average removal efficiencies of Total Nitrogen (TN) (57.6%) and Total Phosphorus (TP) (46.7%) when used to treat the effluent from municipal wastewater treatment plant (Huang et al., 2020). An EFB integrated with tubular reactors, which are filled with biofilm carriers and agricultural waste carbon source (bagasse), showed a stable removal efficiency of 82% for a period of 7 months during treating secondary effluents of wastewater treatment plants (Yang et al., 2020). Sun et al. (2020) stated that denitrification efficiency was nearly 100% with the addition of sufficient electron donors while it was 4-43% without electron donors. EFBs established with complementary substrates (zeolite and sponge iron) efficiently and stably removed N from tail water and the effluent concentration for NH_4^+-, nitrate (NO_3^-) and TN were lower than 1, 1 and 1.5 mg/L respectively (Meng et al., 2021).

Besides, researchers have found that coupling of other technologies such as electrochemical technologies also improved the performance of EFBs. Notably, Yan, et al. (2020) designed an electrolysis integrated EFB with the Mg-Al alloy anode and graphite cathode, placed in the middle of biochar filled polyethylene. This system showed an improvement in removal rates from 26% to 53% and 10% to 76% respectively for TN and TP. The greater removal in integrated EFBs was achieved due to the improved the growth and reproduction of hydrogen autotrophic bacteria and flocculation of PO_4^{3-} with the internally formed Mg^{2+} and Al^{3+} ions. Similarly, EFBs coupled with microbial fuel cell (comprises a biocathode) improved the removal efficiency of NH_4^+ (2-16%) and TN (3-17%) (Yang et al., 2021). These research findings indicate the potential of EFBs for pollution remediation, particularly alleviation of nutrient pollutants. Hence, an in-depth understanding of existing knowledge would be helpful in EFBs related researches to support implementation of this technology. Further, to the best of our knowledge, it is noted that the systematic reviews conducted in this context are limited. Therefore, we attempted to carry out a systematic literature review with the research question; how does an EFB alleviate nutrient pollutants from surface water and two objectives were set. They were (1) to identify the prevailing knowledge on EFBs-based removal of nutrient pollutants from surface water (2) to provide an insight for the means to enhance the performance of EFB for nutrients removal.

II. METHODS

The study used Systematic Literature Review (SLR) process, which consists of three key stages (1) planning (2) conducting review and (3) reporting findings.

A. *Article Selection Process*

Prior to selecting articles, a clear research question was identified in planning stage, followed by a review protocol was developed and validated. The review protocol developed for this study is given in the Table 01. As the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) are preferred for SLRs (Liberati et al., 2009) article selection was carried out as per the PRISMA standards through a series of steps including identification, screening and inclusion. Flow chart depicted in the Figure 01 describes the article selection process performed according to PRISMA guidelines. Briefly, the databases Scopus and Web of Science were used as information sources to identify the studies to be reviewed in SLR.

Table 01: Review protocol

Article selection method	PRISMA guidelines (PRISMA 2020 checklist)
Search term	Ecological Floating Bed
Inclusion criteria	Year range (2010-2023) Document type (Research article) Source type (Journal) Subject area (All) Language (English)
Databases	Scopus (Sc), Web of Science (WoS)
Analysis method	Keyword co-occurrence analysis
Reporting structure	PRISMA guidelines (Overall: PRISMA 2020 checklist, Abstract: PRISMA 2020 checklist for abstract)

The search strategy used in our study was “ecological floating bed”. Screening, a crucial step in article selection process for SLR, was performed two times. Automatic screening was carried out primarily with the titles of articles immediately after identification with the existing limiting options of databases. For this purpose, we choose the year range (2010-2023), document type (article), source type (journal), language (English), subject area (all) as inclusion criteria. Subsequently we retrieved 67 articles from Scopus and 48 from Web of Science. Articles remained after automatic screening were exported into MS Excel sheet which contains a list of information including title, abstract, keywords, journal name, authors name, publication year, number of citations etc. Before performing manual screening, information retrieved in different Excel sheets by database wise, were compiled together and checked for duplicates with the conditional formatting option of MS Excel and then identified duplicates were removed. Then, manual screening was carried out with the exported abstracts against the inclusion criteria and the articles that do not meet the inclusion criteria were excluded. After that, full texts of remaining articles were downloaded and assessed for eligibility to be included in the SLR. During eligibility assessment, the articles that are out of scope, non-relevant and unable to access were excluded. Eventually, the articles found to be sound enough in answering the research question were considered and included for the present study.

B. *Study risk of bias assessment*

Researchers’ bias in selection and analysis of articles affect the quality of review (Kitchenham and Charters, 2007). This was eliminated in the present study by adopting a few measures such as designing and following a protocol briefing the inclusion criteria and analysis methods and systematic, objective selection procedure (Xiao and Watson, 2019; Priyashantha et al., 2022) and independent parallel assessment by more than one researcher (Brereton et al., 2007).

B. *Methods of analysis*

The information in Excel sheet exported from databases were subjected to analysis. Bibliometric analysis was the method of analysis used in the present study, as it is a scientific technique for examining scientific activity in a study (Paule-Vianez et al., 2020). It was performed through Biblioshiny and VOSviewer software. Bibliometric analysis provides scientific maps, commonly known as bibliometric networks. VOSviewer was used to create such maps, where the keywords were considered as the unit of analysis. The relationship between the keywords resulted from their co-occurrences, indicated by the numerous links in the network. VOSviewer visualize this feature in “Keyword co-occurrence network visualization”.

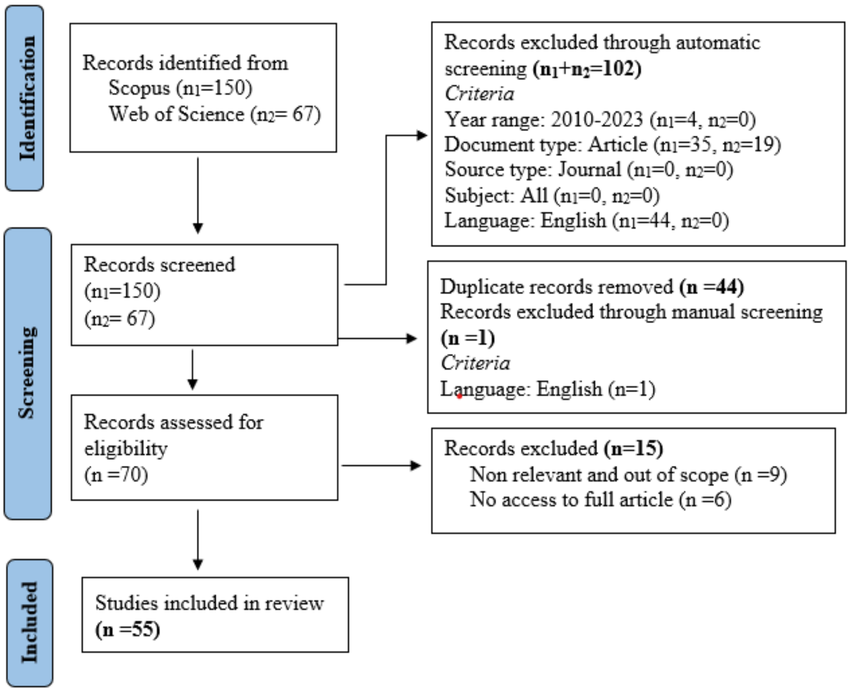

Figure 01: Article selection process

It is necessary to normalize the network visualization so as to gain valuable insight into the area of investigation. So, by default, the VOSviewer produces a two-dimensional network using the association strength normalization. Nodes close to each other indicate strongly related keywords, while nodes far from each other indicate weakly related keywords (Van Eck and Waltman, 2014). A network of clusters was then constructed using the VOSviewer, with nodes related to each other tending to be placed in the same cluster (Chen et al., 2016). Nodes assigned to clusters are indicated by colours in VOSviewer. A cluster may therefore represent a common theme. Since the objectives of our study were to identify the prevailing knowledge and to provide an insight related to application of ecological floating bed in remediation of nutrient pollutants from surface water, the keyword co-occurrence analysis was utilized. In addition, Biblioshiny R software was used to generate preliminary information about the articles included in the review. This includes “year wise published articles”, “country wise published articles”, and “sources of publication”.

III. RESULTS

A. *Study selection*

With the search term “ecological floating bed” 150 and 67 articles were identified respectively from Scopus (Sc) and Web of Science (WoS) databases. Immediately after identification, 4 articles were excluded from Sc identified article set, as they were not in the range of 2010-2023 and no articles were excluded from WoS article set. Then, as per the 2nd inclusion criteria (document type=research article), 35 (conference papers=26, review=7, erratum=1, retracted=1) and 19 articles (proceeding papers=15, review=4) were respectively excluded from Sc and WoS articles’ set. As a result, 111 and 48 articles were respectively retained. Further, as per the 3rd and 4th inclusion criteria, none of the articles were excluded and with the 5th inclusion criteria (language =English), 44 articles were excluded as they were in Chinese language, thus 67 and 48 articles were retained from Sc and WoS articles’ set. Thereafter, a number of duplicated articles (n=44) were removed from whole article set (67+48) and one article was removed during manual screening as it was not in English language. Thus, 70 articles were retained and passed for eligibility assessment, during which full text of each article was independently read by the authors. The articles that are not relevant to the study objectives and unable to obtain full text of articles were excluded. Accordingly, 15 articles were excluded and by the end 55 articles were retained for the review.

B. *Study characteristics*

This section presents the descriptive information of articles used in the review. The Figure 02 shows how the relevant studies are published over the years. It indicates that a very few articles were published till 2017, and afterwards there was an increasing trend in publication and reached the peak in 2021. Then, there was a decline in the publication of articles related to EFBs based pollution remediation. Furthermore, as shown in the Figure 03, the journal named “Science of The Total Environment” is the most popular platform to publish the studies related to EFBs, followed by the journals “Ecological Engineering” and “Bioresource Technology” provided equal opportunities for publishing this kind of studies.

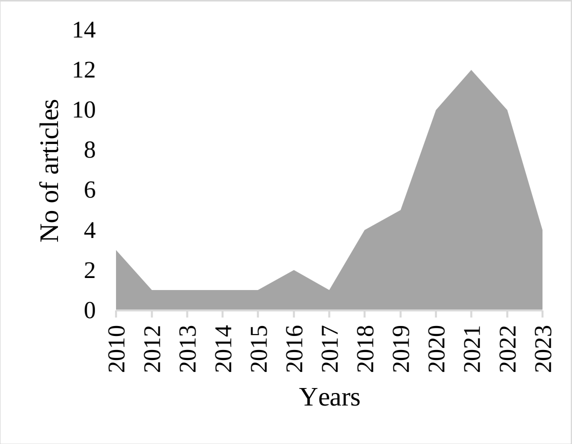

Figure 02: Annual production of articles

Though a number of journals (31) published EFBs based studies, many are considered least popular as they have just published a single article.

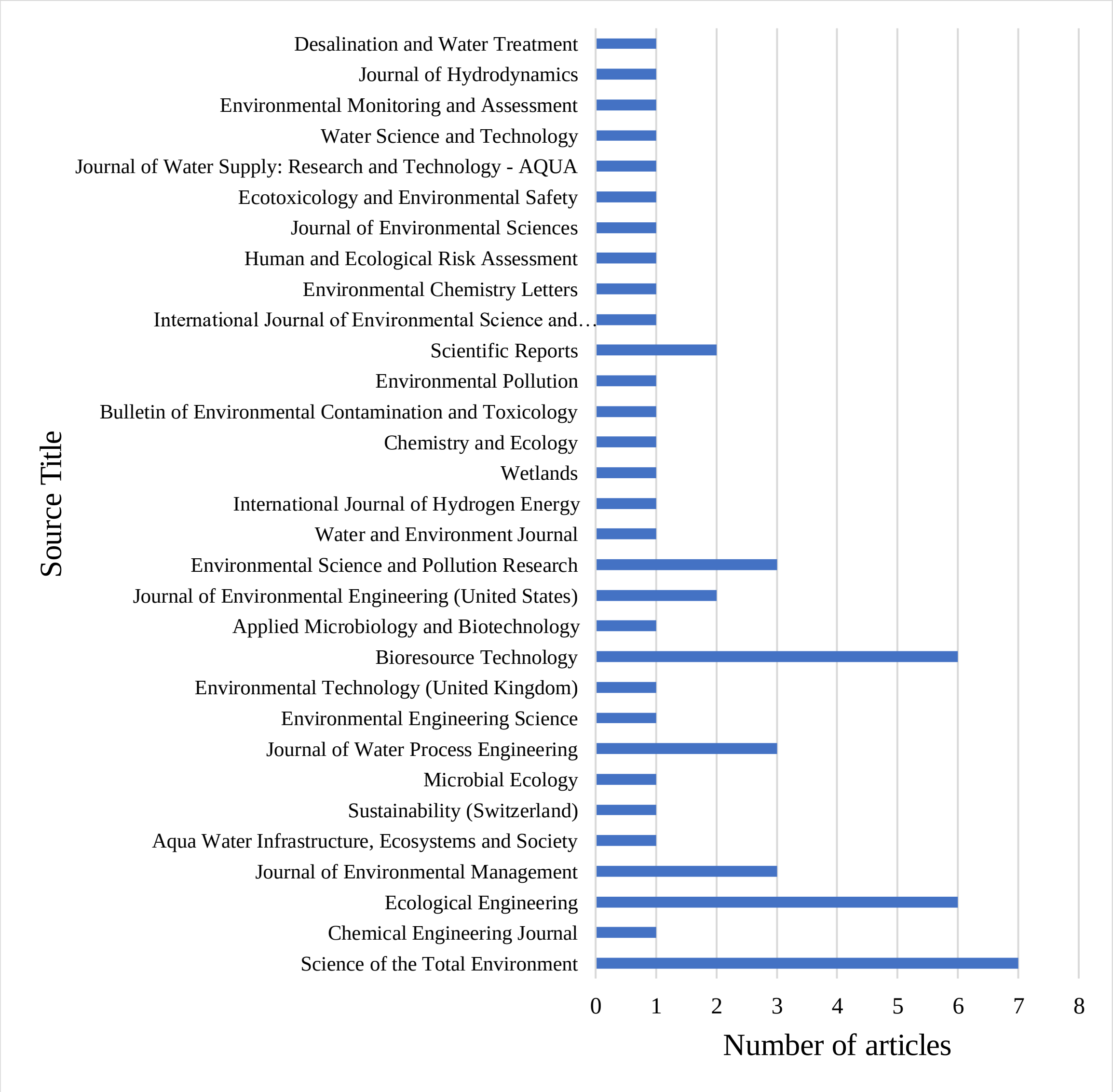

Figure 03: Articles published across different journals

C. Results of studies

This section reports the findings of bibliometric analysis primarily performed with VOSviewer. Results of analysis help addressing the objectives of the study. Thus, the keyword co-occurrence network visualization map (Figure 04) created with the keywords' occurrences, helps addressing the first objective, which was identifying the prevailing knowledge on application of EFBS for remediation of nutrient pollution in surface water. Keyword co-occurrence network visualization map 1 (Figure 04) created with the minimum occurrences of three provide knowledge on certain aspects. The keywords with their respective occurrences are shown in the Table 02. Out of 13, the keywords "nitrogen, ecological floating bed and phosphorous" are the top three frequently occurred, indicated by larger nodes (Figure 04). These keywords have stronger relationship between them and represented by thicker connection line between the nodes. This is justifiable, because N and P are the most promising nutrient pollutants removed by EFBs from the polluted water.

Table 02: Keywords with the corresponding occurrences

Keywords	Occurrences
Absorption	3
Bacteria	12
Denitrification	12
Ecological floating beds	33
Eutrophic water	8
Nitrate	3
Nitrification	5
Nitrogen	36
Phosphate	4
Phosphorus	25
Plant	5
Total nitrogen	3
Total phosphorus	5

Furthermore, the 13 threshold selected keywords are classified into three clusters and denoted in different colours such as green, red and blue. The keywords fall under one cluster are closely related to each other and represent a common theme. Thus, green, red and blue clusters reflect the themes of "nutrient pollutants removed by EFBs", "removal mechanism of N" and "removal mechanism of P" respectively.

The green cluster comprises five keywords namely nitrogen, phosphorous, eutrophic water, total nitrogen and total phosphorous. N and P are the two key nutrient pollutants present in the eutrophic water (Bao 2015; Wu et al., 2016; Yan et al., 2020; Pan et al., 2021; Zhang, T et al., 2021). EFB, as an eco-friendly water treatment technique restores the surface water quality by removing these nutrients to a certain level. The eutrophic water either natural (Li et al., 2010; Zhang et al., 2012; Bao 2015; Wu et al., 2016; Zhang, T et al., 2021) or synthetic (Cui et al., 2018; Yan, et al., 2021; Cheng et al., 2022; Zhao et al., 2022) were successfully treated with this technique. Removal performance of EFBs is investigated by analyzing various forms of these nutrients, whereas the concentrations of TN and TP in polluted water were the more focused ones (Hu et al., 2010; Sheng et al., 2013; Sun et al., 2017; Gao et al., 2020; Huang et al., 2020; Liu et al., 2020).

Red cluster consists of five keywords including ecological floating bed, denitrification, nitrification, nitrate and bacteria. Ecological floating beds, as a bioremediation technique, have been widely employed to remediate various kinds of polluted water including wastewater (Cao and Zhang, 2014; Gao et al., 2020; Peng et al., 2021), secondary effluents (Yang et al., 2020; Sun et al., 2021a, b; Sun et al., 2022) and eutrophic water (Lyu et al., 2020; Zhu et al., 2023). Microbial nitrification and denitrification are the primary pathways of nitrogen removal in EFB systems (Cui et al., 2018; Song et al., 2019; Peng et al., 2023), where the microorganisms especially bacteria, serving as ecological factor, convert the NH_4^+ into NO_3^- and then into N_2 and N_2O, in turn reduce the N load from polluted water.

The blue cluster comprises three keywords such as plant, phosphate and absorption. Nutrients dissolved in water like phosphate are taken up by plants directly. Subsequently, plant absorption is considered as one of the main P removal mechanisms in EFB systems (Samal et al., 2019; Kumwimba et al., 2022; Sun et al., 2022; Zhang et al., 2023).

Ultimately, the network visualization map 1 disclosed the knowledge primarily about the main pollutants removed by EFBs and their mechanisms. There was no information identified regarding objective 2. Thus, the minimum occurrences of keywords were changed into two and keyword co-occurrence analysis was again performed. As a result, 20 threshold keywords were selected and utilized to create the keyword co-occurrence network visualization map 2 (Figure 05), which helped addressing the second objective. The keywords were categorized into three clusters of red, green and blue. The Table 03 shows the keywords grouped into different clusters with their respective occurrences.

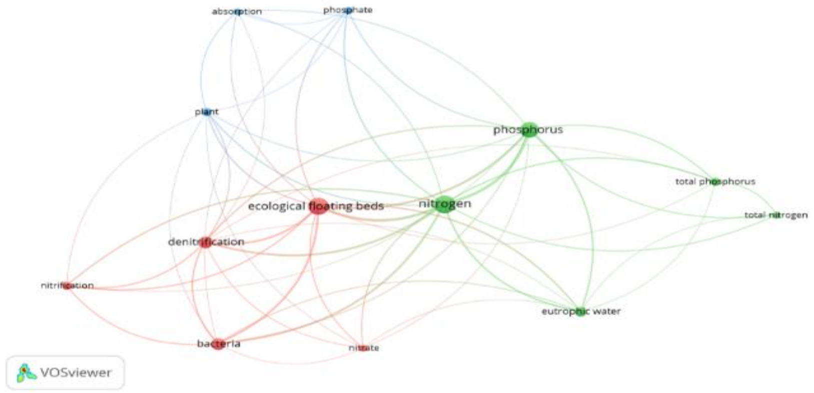

Figure 04: Keyword co-occurrence network visualization map 1

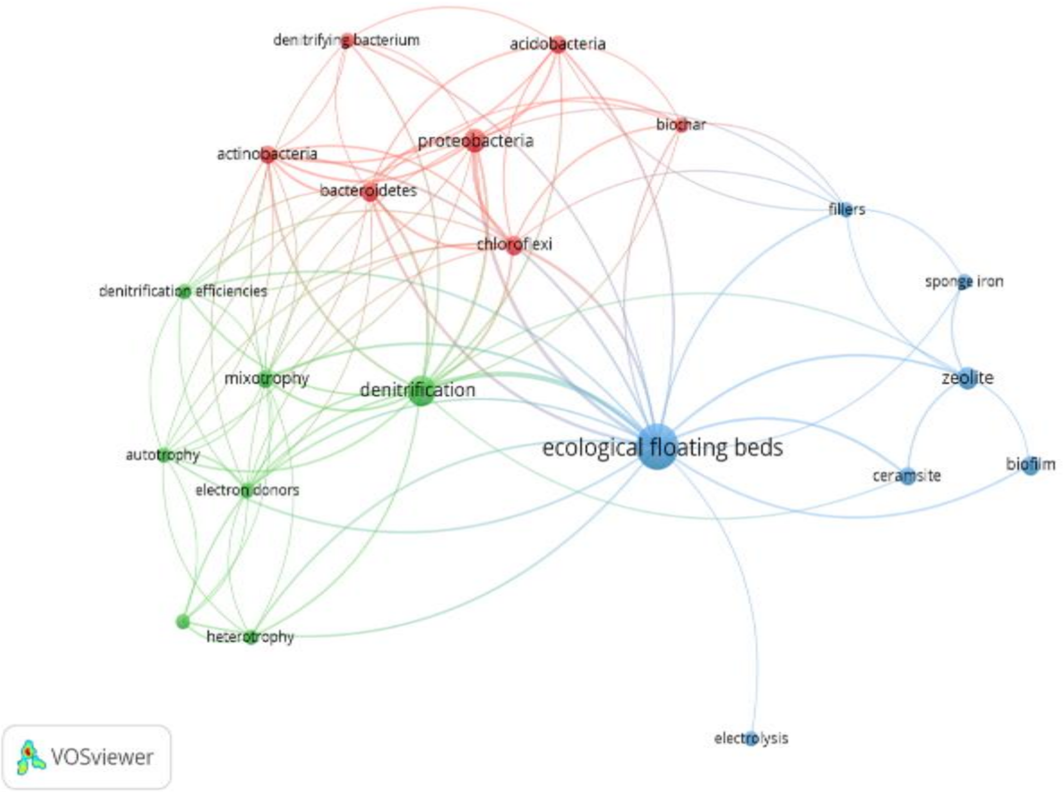

Figure 05: Keyword co-occurrence network visualization map 2

Since denitrification is a main microbial process associated with pollution remediation by EFBs and contributed greatly for N removal from polluted water, keywords related to denitrification are categorized into one cluster (Green). However, inadequate supply of electron donors from organic matters limits the denitrification in EFBs, therefore it is necessary to add electron donors externally to improve denitrification efficiency. Denitrification that occurs in the EFBs are of either autotrophic (Sun et al., 2020; Yan, et al., 2020; Sun et al., 2021a, b) or heterotrophic (Sun et al., 2020; Sun et al., 2021a, b; Cheng et al., 2022; Peng et al., 2023; Qiu et al., 2023) or mixotrophic

(Sun et al., 2020; Sun et al., 2022; Peng et al., 2023), depending on the electron donors involved in denitrification process. Iron scraps, as an autotrophic electron donor, added into the conventional EFBs enhanced the N removal by improving mixotrophic denitrification processes (Sun et al., 2020; Sun et al., 2022; Peng et al., 2023).

Meanwhile, keywords belonging to red cluster reflect the common theme of abundant bacterial phyla. As denoted by larger node in the Figure 05, proteobacteria was found to be the most dominant bacterial phyla involved in N and P removal processes when EFBs are used in bioremediation (Nandy et al., 2022; Kumwimba et al., 2022; Qiu et al., 2022; Liu et al., 2022; Song et al., 2022; Zhang et al., 2023). The other bacterial phyla abundantly present in EFB systems are Bacteroidetes, Chloroflexi, Acidobacteria, Actinobacteria (Nandy et al., 2022; Kumwimba et al., 2022; Zhang et al., 2023).

Though, EFBs are successful in bioremediation, their removal performances were restricted by the growth rate and limited stand biomass of plant (Sun et al., 2009; Wang et al., 2018) and low temperature (Cao et al., 2016). Thereby, inclusion of various physical, chemical and biological materials in EFB systems helped enhancing the performance of EFBs in nutrient pollutants alleviation. Keywords fall under blue cluster namely zeolite (Kumwimba et al., 2022; Zhu et al., 2022), biofilm (Sheng et al., 2013; Pan et al., 2021), ceramsite (Song et al., 2019; Zhao et al., 2022), sponge iron (Wang et al., 2018; Meng et al., 2021; Zhu et al., 2023), fillers (Wu et al., 2016; Song et al., 2022) and electrolysis (Yan et al., 2020; Yan, et al., 2021) are the mostly used materials and processes in EFBs performance enhancement. As these keywords share a common theme, reflecting the means for improving the performance of EFB, those can be regarded as "performance enhancers" of EFBs.

Table 03: Keywords with corresponding occurrences

Cluster	Keywords	Occurrences
Red	Acidobacteria	3
	Actinobacteria	3
	Chloroflexi	4
	Denitrifying bacterium	2
	Bacteroidetes	4
	Biochar	2
	Proteobacteria	6
Green	Autotrophy	2
	Electron donors	2
	Mixotrophy	3
	Heterotrophy	2
	Denitrification	12
	Denitrification efficiencies	2
	Iron scraps	2
Blue	Biofilm	4
	Ecological floating beds	33
	Electrolysis	2
	Ceramsite	3
	Fillers	2
	Sponge iron	2
	Zeolite	5

III. DISCUSSION

The present study was centered answering the research question; how does EFBs remediate nutrient pollutants from surface water? Thus, the first objective was set to identify the prevailing knowledge on EFB-based remediation of nutrient pollutants while second was to provide an insight for the means to enhance the performance of EFB for nutrient pollutants removal from surface water. We identified six themes complying the objectives of the study with the keyword co-occurrence analysis from the keyword co-occurrence network visualization maps 1 and 2 (Figure 04-05). The knowledge identified with
the themes is discussed below in different sub titles.

***Types of pollutants*:** As reflected by the theme 1 (Green cluster in keyword co-occurrence network visualization map 1) the most common nutrient pollutants removed by EFB systems are N and P. Remarkably, 89.7% and 81.2% of TN and 94.4% and 75% of TP were reduced in EFBs planted with water spinach and sticky rice respectively from a polluted tidal river (Sun et al., 2017). EFBs planted with *Canna* and *Calamus* (Cao and Wang, 2014) and *Oenanthae javanica* (Zhou and Wang, 2010) decreased TN concentration respectively from 17 mg/L to 5.23 mg/L and from 12.58 mg/L to 1.16 mg/L. Hence, Zhang, T et al. (2021) reported that EFBs with *Ipomea aquatica* removed TP at a rate of 0.021 mg/L/day. Other than the TN and TP, EFBs were found successful in alleviating the other forms of nitrogen including NH_4^+, NO^{3-}

and PO_4^{3-} (Dai et al., 2018; Lv et al., 2019; Yan, et al., 2021; Ni et al., 2022)

Removal mechanisms: The researchers have declared that volatilization, sedimentation, adsorption, plant uptake and assimilation and microbial degradation and or assimilation are the most promising pathways for nutrient pollutants removal via EFBs (Gao et al., 2017; Sun et al., 2020; Sun et al., 2022). Amongst, microbial degradation (nitrification/denitrification) and plant absorption were found to be the main mechanisms, as reflected by the themes 2 and 3 (Red and blue clusters in keyword co-occurrence network visualization map 1) in traditional as well as functional EFBs. However, in general, contribution of plant absorption for nutrients removal is less (<30%) compare to microbial transformation, especially for N removal. For instance, N removal by plant uptake accounted for 29.3% and 27.8% respectively in floating bed zone and strengthened floating bed zone (Wang et al., 2018). Similarly, the aquatic plants (*Ipomea aquatica*) in the integrated EFBs took up 9.6% of TN to increase their biomass, while it was 8.3% for TP (Zhang, T et al., 2021). These findings confirm the smaller contribution of plant absorption in N removal. However, contradictory results also were observed, in particular, Cui et al., (2018) reported that plant absorption was the main pathway for N removal in conventional (80.5%) and enhanced EFBs (46.3%) with *Cyperus alternifolius* during treatment of hyper eutrophic water. Furthermore, Zhang et al. (2023) recorded a removal of 0.3 kg of P via plant assimilation when treating the rural river with *Oenanthae javanica* planted EFBs. *Oenanthae javanica* plants in EFB absorbed the P from the system and 1.85 g/m^2, 1.65 g/m^2 and 2.11 g/m^2 of TP were accumulated into stem, leaf and root tissues respectively (Zhou and Wang, 2010). Hence, Wang et al. (2018) observed 27.79% removal of P in the floating bed zone of via plant uptake. The nutrient removal via plant uptake primarily depends on plant characteristics (e. g. growth rate) and initial concentration of nutrients (Cui et al., 2018)

On the other hand, microbial degradation played major role in nutrient removal. Especially, N in the polluted water is removed through the processes of nitrification and denitrification, depending on the available N form. For instance, microbial degradation accounted 19.5% and 23.2% for N and P removal in conventional EFBs, while it was 49.9% in enhanced EFBs respectively (Cui et al., 2018).). Furthermore, it was noted that N removal via microbial degradation occurs to a greater extent in EFBs than that of other removal mechanism like plant assimilation, sedimentation etc. For an instance, the N removal via microbial transformation was found to be greater (0.5 g/m^2/d) than the removal via plant uptake (0.02 g/m^2/d) in EFBs with *Myriophyllum aquaticum* (Kumwimba et al., 2022). Similarly, microbial degradation and assimilation accounted 57.2% for N removal in the lake when EFB coupled with microbial electrochemical system was employed, while plant uptake accounted only 1% (Qiu et al., 2023). Out of the two processes of microbial transformation, denitrification is prominent for N removal. Notably, denitrification accounted 72.5% in an integrated EFB, comprised of aquatic plant (*Ipomea aquatica*), aquatic animal unit (*Hyriosis cumingii*) and bacteria-algae unit that used to treat eutrophic water (Zhang, T et al., 2021). Hence, Saunders and Kalff (2001) also stated that 80% of N is removed via denitrification. It is an anaerobic process that occurs at the Dissolved Oxygen (DO) level below 1 mg/L (Tallec et al., 2008) and mediated by denitrifying bacteria either autotrophic or heterotrophic.

Ecological factors involved in nutrients removal: Plants and microorganisms are referred to ecological factors in EFBs responsible for removal of nutrient pollutants from polluted water (Wu et al., 2016). According to the literature available, a wide range of plants have been used in EFBs. *Acorus calamus, Canna indica, Cyperus alternifolius, Ipomea aquatica* and *Iris pseudacorus* are a few widely employed plants in EFBs due to their unique characteristics such as higher removal capacity, cold resistance and landscaping effect (Yang et al., 2020; Nandy et al., 2022; Song et al., 2022; Peng et al., 2023). On the other hand, microbes present in the water, rhizosphere and other materials added into the EFB systems take part in the nutrient removal. As the microbial transformation is being the main route for nutrient removal, various N and P cycling bacteria including ammonifying, nitrifying, denitrifying, oxidizing bacteria involved for N and P removal in EFBs. These bacteria can be of either heterotrophic or autotrophic depending on the source that use to derive the energy (Reflected by the theme 4 in green cluster in network visualization map 2). Furthermore, researchers have investigated how nutrient removal is achieved in EFBs by these microbes. Accordingly, it has been found that the abundance of microbial communities has increased during pollution mitigation accompanied with EFBs (Nandy et al., 2022; Kumwimba et al., 2022; Zhang et al., 2023). As reflected by the theme 5 (red cluster in network visualization map 2), microbes primarily bacteria belonging to phylum “Proteobacteria” were abundantly present in EFBs (Wu et al., 2016; Zhang et al., 2023). This is because the nitrogen cycling bacteria belong to proteobacteria (Chu and Wang, 2016) since microbial degradation (nitrification/denitrification) is the main pathway for N removal. Next to Proteobacteria, Bacteroidetes, Chloroflexi, Actinobacteria and Acidobacteria were found to be the abundant bacterial phyla in EFBs. EFBs not only improve the abundance of microbial communities, but also the richness (Kumwimba et al., 2022), stability (Liu et al., 2022) by providing the essential matters (e. g. oxygen, carbon source and attachment site) for their growth and proliferation and these facets of microbial community are influenced by the season, location, hydraulic properties like flow velocity (Song et al., 2022; Zhang et al., 2023) and physiochemical water quality attributes such as temperature, pH and DO (Read et al., 2015; Mu et al., 2021).

Means to enhance performance of EFB: Since the traditional EFBs rely on aquatic or terrestrial plants, they have certain limitations during bioremediation, primarily their performance is less due to poor growth rate and limited stand biomass of plants (Cui et al., 2018; Liu et al., 2019) and low temperature (Cao et al., 2016). Researchers have studied the alternatives to enhance the performance of EFBs. It was found that various materials added into the conventional EFBs serve as either substrate for growth of plants and microbes or electron supplier, carbon source or attachment site for biofilm growth, in turn increased the pollutant removal (Table 04). Different materials have different capabilities due to their specific characteristics.

As reflected by the theme 6 (Blue cluster in network visualization map 2), zeolite was the frequently investigated material (Cui et al., 2018; Wang et al., 2018; Song et al., 2019; Lin et al., 2019; Zhu et al., 2022; Meng et al., 2021; Kumwimba et al., 2022) for their effect on pollutant removal enhancement. Zeolite as an adsorbent due to its cation exchange, coprecipitation and interception abilities (Wang et al, 2020a, b), showed a good removal of NH_4^+ and PO_4^{3-}. For example, EFB integrated with zeolite and limestone has increased the removal efficiency to 63.5%, 59.3% and 68% respectively for TN, TP and NH^{4+} (Cui et al., 2018). Likely, EFBs suspended with zeolite had a highest purification efficiency of 92.8% for NH_4^+ than the conventional EFBs (46%) (Kumwimba et al., 2022). Meng et al. (2021) also noted the superior effect of EFBs with zeolite for NH_4^+ removal than the traditional EFBs during treating simulated tailwater. Potential of zeolite in EFBs enhancement is extensive as it acts as a biofilm carrier and a filler too and the corresponding applications are discussed in below sections.

Followed by zeolite, biofilm occurred frequently, thus integration of biofilm either inert or biodegradable carriers is considered effective in strengthening the performance of EFBs. In particular, a semi-soft assembly medium (combination of molded plastic ring and polypropylene rayon fibers) as a biofilm carrier was integrated into EFBs with *Ipomea aquatica* and freshwater bivalve and reported to have higher mean removal efficiency of 45.1% and 47.3% for TN and TP respectively (Li et al., 2010). An EFB consisted of hydroponic *Chlorophytum comosum* and biofilm attached to the polymeric fibrous carrier removed 50% of TN and 57% of TP (Pan et al., 2021). In addition to the inert biofilm carriers such as plastics, fibers, elastomeric fillers (Meng et al., 2021) biodegradable or substrate-based biofilm carriers (e.g., rice straw, zeolite, ceramsite, sponge iron, plant litter) found potential in EFBs performance enhancement, as they play multiple roles. These include (i) accommodate the microbes on to their inner and outer surfaces and form biofilm mass (Li et al., 2018; Xiao et al., 2015) (ii) provide organic substrate (C) for microbial metabolism (Nandy et al., 2022) (iii) support plant growth by providing nutrients (Bi et al., 2019). Notably, addition of zeolite helped removal of NO_3^- even at lower temperature (5-15°C) due to higher adsorption of microbes over its larger specific surface area (Meng et al., 2021).

According to the literature, ceramsite, sponge iron and filler materials also received attention to be utilized in strengthening the performance of EFBs. Ceramsite is a material, prepared with direct crushing and burning of natural mineral or industrial waste as raw main material. Li et al. (2018) studied the effects of Ceramsite based Ecological Floating Beds (CFBs) utilizing ceramsite as substrate for macrophytes in aquaculture water quality improvement and reported lower concentration of NH_4^+, TN and TP in CFBs applied ponds than the control ponds without CFBs. Additionally, ceramsite used in EFBs found potential for not only nutrient pollutants alleviation but also in the removal of heavy metals such as V, Cr and Cd (Lin et al., 2019).

In terms of fillers, various types of fillers either organic or inorganic (e. g. biochar, drinking water treatment residual, sponge iron, stereo elastic packing, wood chip, zeolite) have been employed in EFBs through suspending them (Wang et al., 2018; Song et al., 2019; Kumwimba et al., 2022). Recently, it is evident that combination of more than one filler enhanced the performance of EFB rather using single filler due to their complementary effects. For instance, N and P concentrations were lower in the water in the Strengthened Ecological Floating Bed zone (SFB), which was treated with SFB with zeolite and sponge iron (Wang et al., 2018). As reported by Guo et al. (2020), a mixture of zeolite and biochar fillers significantly improved N and P removal. Similarly, EFBs with the combined fillers of zeolite, biochar, woodchip, stereo elastic packing, water treatment residual had highest purification efficiencies for NH_4^+ (99.8%), TN (99.2%) and TP (98.4%) (Kumwimba et al., 2022). In addition to the above-mentioned materials, electrolysis technique also become popular for enhancing the performance of EFBs. Noticeably, lower concentrations of NH_4^+, NO_3^- observed in closed circuit (connected Microbial Electrochemical System (MES)) than those of open circuit, implied that MES enhanced the nutrient removal via EFBs due to enrichment of functional bacteria in a short time during treating urban water in black odorous artificial lake (Qiu et al., 2023).

Table 04 : Materials used to improve the performance of EFB

	Removal Efficiency/Removal Rate (%)					
Materials	**Nitrate**	**Ammonia**	**Total Nitrogen**	**Phosphate**	**Total Phosphorous**	**References**
Freshwater bivalve (*Corbicula fluminea*) and semi soft assembly medium (Biofilm carrier)			45.1		47.3	Li et al., 2010
Dredged sludge		44.3	36.3		35.7	Hu et al., 2010
Fiber fillers	69.5 (62.4)	49.2 (35.3)	49.3 (29.8)			Wu et al., 2016
Zeolite and Sponge iron	72.96 (63.58)	89.98 (77.39)	80.76 (75.80)	92.49 (79.55)	84.44 (73.93)	Wang et al., 2018
Elastic plastic fillers	24.67 (12.04)	77.64 (58.13)				Dai et al., 2018
Mixture of Zeolite and limestone		91.5 (83.2)	82.8 (70.7)		73.9 (67.5)	Cui et al., 2018
Efficient Phosphorus Removal Composite (EPRC) (Prepared with fly ash and steel slag)				0.97(0.87)	0.93(0.83	Liu et al., 2019
Rice straw biocarrier	93.18 (34.54)	93.5 (24.67)	76.94 (34.76)			Cao and Zhang, 2014

Plastic filling (Polymethyl methacrylate)	75.24 (34.54)	19.83 (24.67)	43.94 (34.76)			Cao and Zhang, 2014
Mixture of Iron scraps and Plant biomass	29.14					Peng et al., 2023
Calcium peroxide, Sponge iron	54.72 (9.43)	52.23 (27.27)	59.83 (33.05)	96.55	89.09	Zhu et al., 2023
Rice straw	78	82				Nandy et al., 2022
Zeolite		92.8				Kumwimba et al., 2022
Water treatment residual		88.6				Kumwimba et al., 2022
Biochar		84.2				Kumwimba et al., 2022
Fiber fillers		32.19-55.99	33.89-54.26			Song et al., 2022
Alum sludge ceramsite		58.1 (32.4)	46.7 (27.2)		53.2 (25.8)	Zhao et al., 2022
Embedded pellets of a heterotrophic nitrification aerobic denitrification bacteria (*Pseudomonas* Y1)			73.58 (33.82)			Cheng et al., 2022
Iron scraps (Zero Valent Iron)	50.9 (34)		47.6 (31.2)			Peng et al., 2021
Sodium acetate, Sodium thiosulfate	>90%	15-40%	70-85%			Sun et al., 2021a
Electrolysis (Mg-Al Alloy Anode)		91.2	87.1	96.4		Yan, et al., 2021
Biofilm attached to polymeric fibrous carrier			50		57	Pan et al., 2021
Iron scraps			57-79% (46-56)			Sun et al., 2021b
Electrolysis (Mg-Al alloy anode, graphite cathode)		96.5 (94.5)	53.1 % (26.7)	74.5 (8.9)	76.5 (10.54)	Yan et al., 2020

IV. SUPPLIMENTARY INSIGHTS

A. *Factors influencing nutrient removal in EFB*

1) *Temperature*

Temperature is one of the extrinsic factors that influences nutrient removal performance of EFBs, as the physiological and biochemical activities of plants and microorganisms are temperature dependent. In terms of N removal, both nitrification and denitrification are temperature sensitive. The conducive temperature for nitrification is 25-30°C (Wang et al., 2018), where the survival of nitrite oxidizing bacteria is optimum. Temperature shows positive correlation for denitrification (Sun et al., 2020), and 20-30°C was found to be optimum for denitrification (Sun et al., 2020; Sun et al., 2022; Peng et al., 2023) as it is conducive for growth and activity of denitrifying bacteria. The extremes of temperature (low and high) affect these microbial processes and lead to reduced N removal. For example, higher temperature (>30°C) observed during stage II impaired the nitrification and resulted lower NH_4^+ and TN removal in EFBs coupled with microbial fuel cells (Yang et al., 2021). Further, lower temperature (<25°C) observed in phase V, resulted lower TN removal efficiencies in traditional EFBs and functional EFBs with electron donors due to reduced denitrification (Sun et al., 2021b). Likely, poor denitrification due to limited growth and activity of denitrifying bacteria was observed in EFBs at lower temperature (<20°C) (Sun et al., 2022; Peng et al., 2023). Sun et al. (2021a) also observed a decline in TN removal efficiencies in EFBs enhanced with electron donors at lower temperature (<20°C), even though the Hydraulic Retention Time (HRT) was 3 days. Furthermore, temperature indirectly affects the DO and both are inversely proportional to each other. Thus, denitrification become poor at lower temperature due to higher DO as it competes with NO_3^- for electrons during reduction process, where denitrification is strictly anoxic (<1 mg/L DO) (Tallec et al., 2008). Poor denitrification at lower temperature as a result of higher DO was observed by Peng et al. (2023) and Sun et al. (2021a, b). To cope up these adverse effects of temperature, addition of many materials including iron scraps (Sun et al., 2021b), sponge iron (Meng et al., 2021), porous carriers like zeolite (Song et al., 2019; Meng et al., 2021) and extension of HRT (Yang et al., 2021), have been found possible means to improve the nitrogen removal.

2) *HRT/ Water Exchange Period*

HRT simply refers to the time interval over which the water is retained without changing inside the reactors/containers/digestors. This influences nutrient removal by affecting the contact between the nutrients in the water and microbes. The effects of HRT on nutrient removal in EFBs were studied by a few numbers of researchers. In particular, Li et al. (2010) evaluated the effects of water exchange on purification efficacy of an integrated EFBs (IEFBs) employing plant, fresh water clam and biofilm carrier. They evidenced an increase in removal efficiency for TN (26.3-52%) NH_4^+ (19.7-33.7%) and TP (32.8-54%) with the increase in water exchange period from 3 to 5 days. This is because that the assimilation of nutrients (N and P) by plants, microbes and bivalves, microbial degradation of N and inorganization of particulate P could be enhanced in prolonged water exchange period. Similarly, TN removal efficiencies of EFBs suspended with fillers such as iron scraps and plant biomass also increased by 20% when the HRT extended to 3 days from 2 days (Peng et al., 2023). Moreover, a decline in effluent concentrations for NH_4^+, NO_3^- and TN was observed from 1.4-0.3 mg/L, 6.5-2.6 mg/L and 8.2-3.2 mg/L respectively with the increase in HRT 1-3 days and highest TN removal occurred at 3 days HRT in iron based EFBs (Sun et al., 2022). Sun et al. (2021a) also noted that regardless of the electron donor used, more N removal occurred in 3 days HRT than that of 2 days HRT. These findings imply that HRT of 3 days is conducive to complete denitrification and higher N removal can be achieved at this HRT at a temperature around 21°C, if the influent has a good mixture of NH_4^+ and NO_3^-.

On the other hand, it was found that the higher nutrient removal is possible even at shorter HRT when other physiochemical parameters especially temperature and DO substantially influence the effects of HRT. For instance, the higher water temperature (26.8°C) observed during 1 day HRT, resulted more N removal due to increased denitrification when NO_3^--N was the main constituent in influent (Sun et al., 2021a). Hence, Sun et al. (2021b) also reported the similar effects of HRT on performance of EFBs for N removal, which means effluent NO_3^- content was low (2.74 mg/L) at 3 days HRT in EFB supplemented with iron scraps. However, due to higher water temperature, effluent $NO_3^-$was low (6.55 mg/L) at 1 day HRT than at HRT of 2 days (7.18 mg/L).

3) *Forms of influent N*

N in the raw water comprises of NO_2^-, NO_3^-, NH_4^+ and each form of N is removed via different routes, primarily NO_3^- via denitrification and NH_4^+ either via nitrification or plant uptake. A very few studies focused investigating the effects of influent N form on its removal performance of EFBs. In particular, Sun et al. (2021b) observed higher TN removal when the main influent N was NO_3^-, implying that NO_3^- nitrogen removal via denitrification contributed more for TN removal. Further, with the decrease in influent NO_3^- (vice versa in NH_4^+), there was a decline in TN removal efficiency in both traditional (56-46%) and functional EFB (79-57%) due to reduced NO_3^- load for denitrification. A decline in NO_3^-removal was observed by Sun et al. (2022) with the decrease in influent NO_3^-. Similarly, Sun et al. (2021a) also observed a decrease in TN removal in EFBs added with different electron donors such as sodium acetate (79-49%), sodium thiosulfate (81-46%) and iron scraps (79-46%) with the increase and decrease of influent NH_4^+- and NO_3^- respectively. Further, with the increase in influent NH_4^+-, N removal pathway changed to nitrification and ammonium nitrogen removal increased. A higher NH_4^+ removal resulted a higher TN removal (35% higher than that of NO_3^--based influent) when the main influent nitrogen was NH_4^+ (Dai et al., 2018). From these results, it is noteworthy to conclude that, depending on influent forms of N, different N removal routes dominate and contribute to TN removal. Accordingly, denitrification is the dominant pathway when the influent has higher NO_3^-, while nitrification dominates in the influent with higher NH_4^+ for TN removal. In general, TN removal occurs via the combination of nitrification and denitrification and to achieve a good TN removal efficiency, there should be a mixture of NH_4^+ and NO_3^-in water. Moreover, in addition to N load, the operational conditions including pH, temperature and DO influence the contribution of each pathway.

VI. CONCLUSION

The nature-based bioremediation technique called EFBs removes the nutrients pollutants especially different forms of N and P from various polluted water sources. As the plants and microbes are the two main ecological factors involved in EFBs, the plant assimilation and microbial degradation processes dominate the removal mechanisms of these nutrients and contributed to a greater percentage of removal. The performance of EFBs is not consistent always and exhibit a wider range of efficiency for pollutants removal subjecting to variation in the type of water being treated, type of plants employed in EFBs and the operation conditions such as temperature, DO level, HRT etc. Furthermore, inclusion of various materials has found enhancing the performance of EFBs, whereas the zeolite is the widely utilized material. Besides, during this study, secondary pollution from decaying plant components and sediment and plant lodging were identified as the major challenges in EFBs based water treatment. This can be minimized through the frequent harvesting of plant biomass and stabilization of nutrients in sediments.

Even though, this study has comprehensively expressed the existing knowledge of EFBs, restricted article search for open access and two databases are considered limitations of this study which open an avenue for future studies. Further, it was noted that EFBs have not been utilized well by the developing countries in water treatment due to lack of community awareness, knowledge, skills, facilities and responsible authorities. Therefore, considering the potential benefits of EFBs in pollution remediation, it is advised to promote their applications though the awareness campaigns at smaller and larger levels. Further, young generation should be motivated and provided with in-hand training for efficient designing and handling of EFBs. By addressing the limitations and challenges, application of EFBs as well the benefits attained from this kind of study can be expanded in future.

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