World Journal of Microbiology and Biotechnology (2020) 36:151
https://doi.org/10.1007/s11274-020-02926-y

REVIEW

Simultaneous nitrification–denitrification by phosphate accumulating microorganisms

Shivani Shukla[1] · **Ankita Rajta**[1] · **Hema Setia**[1] · **Ranjana Bhatia**[1]

Received: 15 April 2020 / Accepted: 5 September 2020 / Published online: 14 September 2020

Abstract

Nitrogen and phosphorous are important inorganic water pollutants that pose a major threat to the environment and health of both humans and animals. The physical and chemical ways to remove these pollutants from water and soil are expensive and harsh, so biological removal becomes the method of choice to alleviate the problem without any side effects. The identification of microorganisms capable of simultaneous heterotrophic nitrification and aerobic denitrification has greatly simplified the sequestration of nitrogen from ammonium (NH_4^+) into dinitrogen (N_2). Further, the discovery of phosphorous accumulating organisms offers greater economic benefits because these organisms can favourably and simultaneously remove both nitrogen and phosphorous from wastewaters hence reducing the nutrient burden. The stability of the system and removal efficiency of inorganic pollutants can be enhanced by the use of immobilized organisms. However, limited work has been done so far in this direction and there is a need to further the efforts towards refining process efficiency by testing low-cost substrates and diverse microbial populations for the total eradication of these contaminants from wastewaters.

Keywords Nitrification · Denitrification · Simultaneous heterotrophic nitrification-aerobic denitrification · Phosphorus uptake · Phosphorus accumulating organisms · Wastewater

Introduction

Increasing population and subsequent industrialization over the past decades has created new challenges for the environment. Every day, an enormous amount of waste from industries, agricultural reforms, mining activities, chemical fertilizers, pharmaceutical production plants, hospitals, landfills, and communal individuals is being disposed of into rivers and oceans (Khalaf 2016). This has increased the level of unwanted organic and inorganic material in the waters, causing pollution to exorbitant levels. As a consequence of this unjustified pollution, the crucial biogeochemical cycles of nitrogen and phosphorus have been extremely disturbed (Ahlström and Cornell 2018). Nitrogen mainly in the form of nitrate (NO_3^-) and phosphorous in the form of phosphate (PO_4^{3-}) has become the most common inorganic pollutants that have entered the water bodies.

The impact of these pollutants is profound and may prolong for many years (Ahlström and Cornell 2018). High levels of nitrate pose extensive health hazards such as methemoglobinemia, thyroid problems, respiratory problems, tumours, etc. to humans and animals (Rajta et al. 2019). Nitrate and phosphate amalgamation in the aquatic ecosystems leads to eutrophication causing an increase in biomass in the form of algal blooms, phytoplankton, and macrophytes. This adulteration changes the color of rivers, lakes, and the marine environment (Yang et al. 2016), reduces penetration of oxygen and light, and results in the deaths of aquatic life. This completely upsets the ecosystem balance and deteriorates the quality of water.

Nitrate is naturally available due to the processes of nitrification and mineralization of organic matter in the soil (Rajta et al. 2019). It is usually present in optimal concentrations (Lockhart et al. 2013), however, being very soluble and mobile, its excessive amounts can easily seep from the surface into groundwater and accumulate for decades causing adulteration of drinking water (Guadie et al. 2013). Excessive nitrate originates from agricultural sources such as nitrogen-based fertilizers, waste tips, manure collected from the farming industry, landfills as well as non-agricultural

---

✉ Ranjana Bhatia
ranjanabhatia20@gmail.com

[1] Department of Biotechnology, University Institute of Engineering and Technology, Panjab University, Chandigarh 160014, India

sources such as combustion of fossil fuels, domestic waste and industrial discharge (Savci 2012). Phosphorous is a non-renewable resource but its agricultural utilization is inefficient. Large amounts of dissolved phosphorous (orthophosphate form) are lost to the soil and water bodies even though restricted inflow in water bodies is necessary to maintain high biodiversity. Non-point, anthropogenic sources such as natural decomposition of rocks and minerals, erosions, agricultural runoff, and point sources such as household contributions including human waste, laundry cleaners, household cleaning products and industrial waste (Parsons and Smith 2008; Elser 2012) are responsible for phosphorus overload in surface and ground waters beyond ecological relevance.

Removal of nitrate and phosphate is undoubtedly a priority concern in wastewater treatment to retain the quality of open and ground waters (Fabro et al. 2015). Microorganisms mediated simultaneous remediation of both is an environment-friendly and efficient strategy. The process is self-sustaining and has economical benefits as more than one pollutant can be targeted by the same microorganism. However, not much has been achieved so far in this direction and the process is still in its nascent stage of development.

This review describes the process of simultaneous nitrification–denitrification and phosphorous removal (SNDPR) by aerobic microorganisms. Diverse microbial types that can perform different enzyme-mediated conversion reactions of nitrogen and phosphorous and the influencing factors are also discussed. Finally, a model for the process of SNDPR has been proposed. Previous reviews (Nancharaiah et al. 2016; Winkler and Straka 2019) have mainly focussed on nutrient removal from wastewaters by the combined application of biological and bio-electrochemical treatment systems to minimize energy requirements. Their large scale implementation is still awaited. This review enables a better understanding of the microbial process per se and describes the progress and lacunas in the simultaneous removal of nitrogen and phosphorous from contaminated waters by biological means.

Treatment technologies for environmental pollutants

Untreated waters coming from various sources may contain high doses of contaminants such as calcium, iron, lead, chloride, magnesium, fluoride, phosphate, and nitrate (Sharma and Bhattacharya 2017). These wastewaters can be treated by different physical, chemical, and biological methods. Physical methods involve the application of physical forces. Clarifying the effluents by filtration, flocculation, floatation, and mixing (Topare et al. 2011) are some of the physical methods. Chemical methods involve the addition of chemicals. Chemical precipitation, chemical oxidation, and advanced oxidation are some of the chemical-based methods (Topare et al. 2011; De-Bashan and Bashan 2004). Biological treatment involves the breakdown of organic and inorganic wastes by several anaerobic and aerobic microorganisms such as nitrifiers and denitrifiers (He et al. 2016b), converting them into gaseous forms. The chemical method is most appropriate for dealing with toxic inorganic compounds. But, in turn, it further increases the chemical load of the waters. Moreover, these processes do not completely remove nitrogen and phosphorus from surface and groundwater. Their success rate depends upon the type of operation and other impurities found in water (Carolin et al. 2017). As such, the biological approach is most acceptable for the complete removal of nitrogen and phosphorous compounds. A description of the various treatments and their advantages and disadvantages are summarized in Table 1.

Microbial proficiency for nitrogen removal

Microorganisms are the main biological components that help to remove nitrogenous pollutants from wastewater. Nitrification and denitrification are the two most important processes involved in its biological treatment (Rajta et al. 2019). Conventionally, treatment methods were based on autotrophic nitrification and anaerobic denitrification. These were time-consuming and energy-intensive methods (Khardenavis et al. 2007) and involved treatment with different microorganisms having differing requirements for oxygen and electrons (Wan et al. 2017). In recent times, bacteria with a vast potential for treatment and removal of nitrogen under a variety of environmental conditions have been identified. These include diverse nitrifiers, denitrifiers, and those that can participate in simultaneous nitrification and denitrification (SND) (Bai et al. 2019). Identification of these microorganisms has revolutionized the wastewater treatment technology making it faster and more proficient than the conventional methods.

Nitrification implies the biological oxidation of ammonium (NH_4) to nitrate (NO_3) under strict aerobic conditions (Thakur and Medhi 2019). Till the identification of complete ammonia oxidizers (Cotto et al. 2020), it was considered to be a two-stage process performed by different groups of organisms. The first stage of ammonia oxidation can be carried out by the autotrophic ammonia-oxidizing bacteria (AOB) and mixotrophic archaea and the second stage is performed by the nitrite-oxidizing bacteria (NOB). Ammonia oxidizing archaea (AOA) predominate over the AOB in many environments, especially in extreme conditions, possess a higher affinity for oxygen and ammonia (Winkler and Straka 2019), and account for vigorous ammonia oxidation (Hou et al. 2013). AOA mainly belong to phylum *Thaumarchaeota* with *Nitrosopumilus maritimus* and

Table 1 Treatment technologies for removal of environmental pollutants from wastewater

Method	Advantages	Disadvantages	References
Physical methods			
Membrane filtration Nanofiltration (NF) Ultrafiltration (UF)	Simplest method of separation Produces quality effluent No chemicals requirement Eradicates every single type of salts, mineral by-products, and dyes Low solid waste generation	Membrane filtration design could differ perceptively Investment cost very high for a start-up for small industries High energy requirement	Crini and Lichtfouse (2019)
Irradiation Electron beam and radiation	Simplest and efficient method Reduces the colour of sewage plant	Difficult recovery on a large scale High cost of maintenance and operation	Anjaneyulu et al. (2005)
Adsorption	Economically feasible process Produces a quality product Adsorbents can be made from low-cost waste materials High removal efficiency	Post-treatment disposal Requirement of large quantity	Ahmed et al. (2017)
Coagulation	Ability to inactivate bacteria Accessibility of diversity in viable chemicals Good capital cost	Increased volume of sludge High cost Low exclusion of arsenic	Bratby (2016)
Chemical methods			
Chemical precipitation	Economical Effective at removing metals and fluorides Lack of selectivity of the metal greatly reduces the demand for Chemical oxygen	Futile removal of metal ions in low concentrations Generation of a large amount of sludge treatment Disposal problems	De-Bashan and Bashan (2004); Crini and Lichtfouse (2019)
Chemical oxidation	Simple, efficient and speedy process. No sludge production Oxidation helps to eliminate colour and odour	Unidentified intermediates formation Requirement of chemicals Chemical oxidation releases some volatile compounds	Bratby (2016)
Advanced oxidation processes (AOP)	Rapid degradation Effective for dyes, drugs, etc. No sludge generation	Expensive Not used at small level industries By-product formation	Parsons (2004)

Table 1 (continued)

Method	Advantages	Disadvantages	References
Electrochemical technologies Electro-coagulation (EC) Electro-oxidation (EO) Electro-flotation (EF)	High removal efficiency Cost-effective Compact facility for treatment Anodic oxidation doesn't require a large number of chemicals	Requires chemicals for flocculation and coagulation High cost of yearly upkeep Deposition of sludge can slow down electrolytic properties in continuous operation Efficiency of separation depends on bubble size in EF	Chen (2004)
Biological methods			
Constructed wetland systems	Cost-effective approaches and simple techniques are involved to design it High constancy in wildlife habitats as well as changes in environmental situations. Long life	High energy demands Excessive production of sludge	De-Bashan and Bashan (2004); Lee et al. (2009); Zhang et al. (2015)
EBPR by activated sludge	Cheap, effective and acceptable way to eliminate phosphorus	Insufficient carbon source issues	Cai et al. (2019)
Immobilization of biologicals	High Alteration rate due to cell stacking densities. increased testability resistance of microbes to the outer environment	Chemically stable organic adsorbents whereas inorganic adsorbents are soluble in alkaline solution. High leakage rate	De-Bashan and Bashan (2010); Abdel-Raouf et al. (2012); Bouabidi et al. (2019)
Microalgae treatment	Biomass is used as a fertilizer	Seasonal variation in efficiency	Matamoros et al. (2015)

Nitrososphaera viennensis as the dominant species (Limpiyakorn et al. 2011). Ammonia oxidizing bacteria (AOB) carry out the oxidation of ammonia to hydroxylamine by the enzyme ammonia monooxygenase (AMO) and hydroxylamine is further oxidized by hydroxylamine oxidoreductase (HAO) to nitrite. Nitrite is converted to nitrate by the nitrite oxidase enzyme of the nitrite oxidizers (NOB) (Lei et al. 2016). Ammonia oxidizing archaea possess the AMO genes but lack the HAO genes which catalyze the hydroxylamine oxidation process. Heterotrophic nitrification involves the oxidation of both inorganic and organic forms of nitrogen to nitrates by various heterotrophic bacteria (Stein 2011). In some of these microorganisms, the mechanism of ammonia oxidation is the same as in autotrophic ammonium oxidizing bacteria (AOB). This is supported by the observation of structural and functional similarity in the ammonia monooxygenase and hydroxylamine oxidoreductase enzymes of heterotrophic nitrifiers, most particularly *Paracoccus pantotrophus* GB17*,* with that of ammonia-oxidizing bacteria (AOB) (Yokoyama et al. 2012). Other heterotrophic organisms may carry out the oxidation of hydroxylamine by the cytochrome P460 (Zahn et al. 1994). The final step involving oxidation of nitrite to nitrate is catalyzed by the catalase enzymes (Stein 2011).

Comammox or the complete ammonia oxidizers are autotrophic organisms that catalyze the complete conversion of ammonia to nitrate by employing ammonia and nitrite as electron donors (Cotto et al. 2020). These organisms are found in both terrestrial and aquatic habitats and involve similar enzyme-catalyzed reactions as the AOB/AOA and NOB. However, the ammonia monooxygenase enzyme is phylogenetically distinct from that found in AOB and AOA (Daims et al. 2015). Sublineage II of genus *Nitrospira* is the distinctive branch responsible for complete nitrification. Comammox bacteria have a high affinity for ammonia and oxygen but a slower growth rate and offer great advantages in energy-saving and nitrogen polishing (Lawson and Lücker 2018; Ren et al. 2020).

Anammox is an anaerobic process in which anaerobic ammonia-oxidizing bacteria use nitrite or nitrate as an electron acceptor to oxidize ammonium nitrogen to molecular nitrogen (Abbassi et al. 2014). These bacteria belong to the phylum *Planctomycetes* and include five genera identified to date that play a vital role in the nitrogen cycle. These include *Candidatus* Brocadia, *Candidatus* Kuenenia, *Candidatus* Jettenia, *Candidatus* Scalindua*,* and *Candidatus* Anammoxoglobus (Nancharaiah et al. 2016; Ren et al. 2020). Initially, half of the available ammonium is oxidized to nitrite by oxygen. In anammox, this nitrite then acts as an electron acceptor and converts ammonium to nitrogen via the formation of two intermediates, nitric oxide (NO) and hydrazine (N_2H_4) (van Niftrik and Jetten 2012; Nancharaiah et al. 2016). The key enzymatic players in anammox are the nitrite reductase (NIR), hydrazine synthase (HZS) and the hydrazine dehydrogenase (HDH). It is mainly an autotrophic process with a high affinity for ammonium and less release of greenhouse gases (Ren et al. 2020) making it more effective than both nitrification and denitrification.

Aerobic denitrification, on the other hand, converts nitrate into gaseous nitrogen in a series of enzyme guided steps, nitrate reductase being the first enzyme of the pathway (Rajta et al. 2019). Here, co-respiration is an important mechanism where oxygen and nitrate are simultaneously used as electron acceptors (Chen and Strous 2013). In some aerobic microorganisms mechanism of heterotrophic nitrification is clubbed with aerobic denitrification (Fig. 1). Heterotrophic genera capable of SND include *Alcaligenes* (Joo et al. 2005), *Bacillus* (Kim et al. 2005), *Diaphorobacter* (Khardenavis et al. 2007), *Providenica* (Zhao et al. 2010), *Achromobacter*, *Comamonas, Agrobacterium* (Chen and Ni 2011), *Pseudomonas* (Qiu et al. 2012; He et al. 2018; Zhang et al. 2019; Su et al. 2019), *Serratia* (Huang et al. 2017), *Enterobacter* (Wan et al. 2017), *Rhodococcus*, *Klebsiella* (Su et al. 2019), *Acinetobacter* (Xia et al. 2020). These microorganisms have several advantages such as a high growth rate and their individual ability to convert ammonium (NH_4^+) into nitrogen (N_2). Identification of these microorganisms has made nitrogen removal from wastewaters simpler as nitrification and denitrification can be performed at the same time under the same set of conditions. While the comammox organisms can potentially shorten the process of simultaneous nitrification–denitrification, their activity may be limited by the presence of organic pollutants in wastewaters. Ammonia oxidizing archaea, on the other hand, can contribute only to ammonium oxidation during SND (Wang et al. 2017). Anammox organisms can be very useful for the complete removal of nitrogenous substances with limited requirements. However, their potential is restricted by their extremely slow growth rate with a doubling time of 11 days or even more (Lan et al. 2011) making process development quite difficult.

As such, simultaneous heterotrophic nitrification-aerobic denitrification becomes the process of choice for the treatment of wastewaters with a considerable organic load. However, there are differences in the biochemical routes followed by different bacteria capable of SND and this makes it very tough to draw generalizations. For example, although denitrifying enzymes are found in *Thiosphaera pantotropha*, nitrate reductase is absent in *Alcaligenes faecalis* (Chen and Ni 2011) even though it performs SND. Therefore, it is important to identify a wider range of organisms with potentially enhanced abilities and pathways for SND (Zhao et al. 2010).

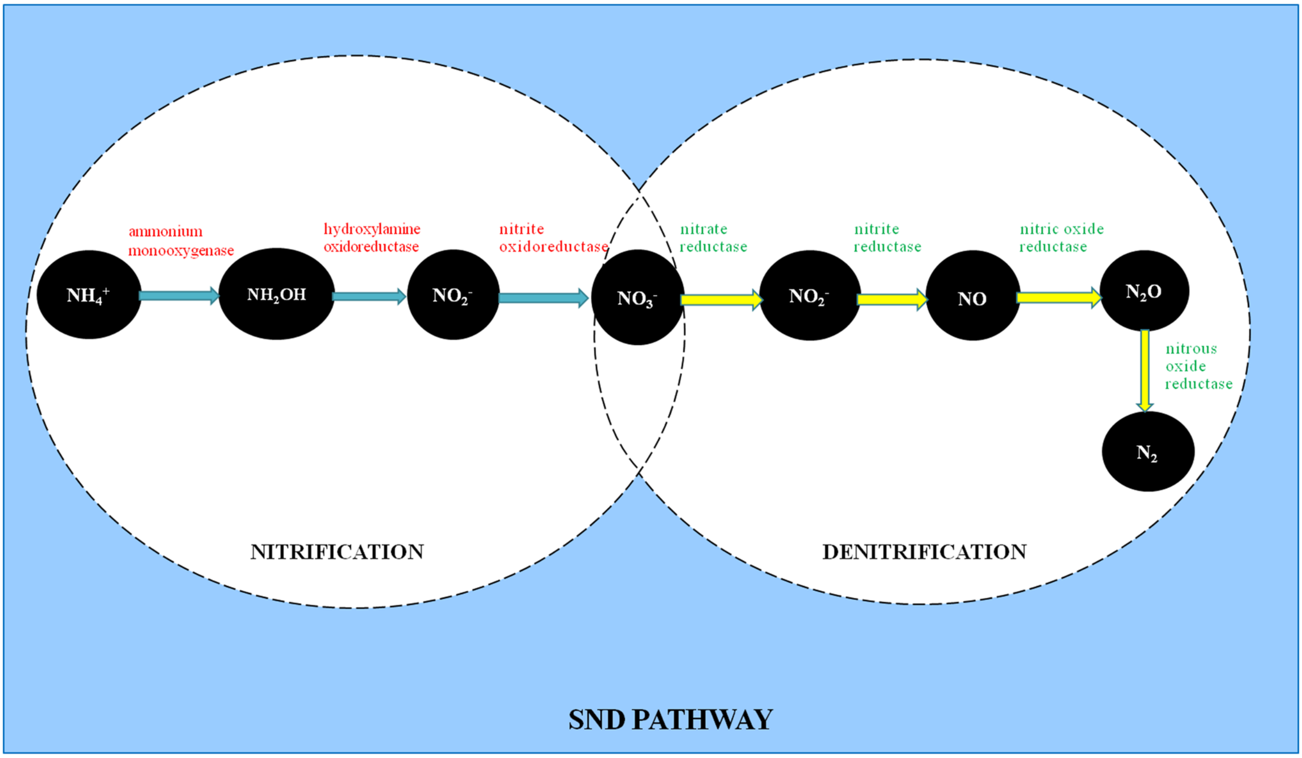

Fig. 1 Simultaneous nitrification–denitrification pathway in bacteria

Factors Affecting Simultaneous Nitrification–Denitrification

The activity of different organisms involved in nitrogen removal is mainly dictated by environmental conditions. Type of carbon source, C/N ratio, temperature, pH, and levels of dissolved oxygen have a significant influence on nitrogen removal by SND bacteria. Accordingly, the effect of these parameters on simultaneous nitrification–denitrification has been widely investigated.

On the way to accomplish simultaneous heterotrophic nitrification and aerobic denitrification, several carbon sources such as glucose, succinate, acetate, sodium citrate, mannitol, trehalose, and glycerol have been reported for different bacteria including *Pseudomonas* (Yang et al. 2016), *Enterobacter cloacae* (Guo et al. 2016), *Anoxybacillus contaminans* (Chen et al. 2015b), *Paracoccus denitrificans* (Medhi and Thakur 2018), *Bacillus cereus* (Barman et al. 2018), *Pseudomonas putida* (Zhang et al. 2019), *Acinetobacter* sp. (Xia et al. 2020). Wan et al. (2017) used six different carbon sources (glucose, sucrose, mannitol, formic acid, trehalose, and sodium acetate) on *Enterobacter cloacae* HW-15 for SND activity and observed sodium acetate to be the most efficient carbon source. Similarly, Rout et al. (2017) reported 94% NH_4-N, 97% NO_3-N, and 84% NO_2-N removal in 36 h by *Bacillus cereus* GS-5 using sodium acetate as a carbon source. Glucose was judged as the best carbon source for *Paracoccus denitrificans* ISTOD1 and *Bacillus cereus* (Medhi et al. 2017; Barman et al. 2018). Appropriate carbon source helps to attain a high rate of growth and nitrogen removal in simultaneous heterotrophic nitrification–denitrification. Besides this, the concentration of carbon directs the flow of electrons in the process of nitrogen removal. Therefore, SND is also influenced by an optimum C/N ratio. Extremely low or high C/N ratios can adversely affect the process efficiency by inhibiting the growth of bacteria (Chiu et al. 2007). So far, a C/N ratio between 8 and 10 has been reported for efficient SND (Xia et al. 2020).

Many findings have confirmed that when the level of dissolved oxygen (DO) exceeds its critical value the process of nitrogen removal by aerobic bacteria gets blocked. For example, Hocaoglu et al. (2011) investigated the effects of dissolved oxygen on simultaneous nitrification and denitrification in membrane bioreactors and found that best nitrogen removal could be achieved between dissolved oxygen levels of 0.15 to 0.35 mgL^{-1}. Further increasing the oxygen concentration significantly reduced the effectiveness of nitrate removal. Jin et al. (2015) have reported DO value between 0.3 and 0.8 mgL^{-1} as most effective for SND whereas, Li et al. (2018a) carried out simultaneous nitrification and denitrification at 1.2 mgL^{-1} DO. It is important to maintain DO levels according to specific strain requirements (Barman et al. 2018). Lei et al. (2019) and Xia et al. (2020) reported 6.08 mgL^{-1} to be the best dissolved oxygen concentration for *Ochrobactrum anthropic* LJ81 and *Acinetobacter* sp. ND7, respectively. Therefore the level of dissolved oxygen is critical for simultaneous heterotrophic nitrification-aerobic denitrification process. Temperature is another important factor that impacts the metabolic motion of the organism and improves the reaction rate in simultaneous heterotrophic nitrification-aerobic denitrification (Guo et al. 2013). Most SND bacteria are sensitive to variations in temperature and perform best within a temperature range of 25–37 °C (Rout et al. 2017; Zhang et al. 2019; Xia et al. 2020). A longer lag phase and interruption in gene expression were observed in SND capable *Pseudomonas mandelli* when grown at 10 °C (Lakha et al. 2009).

One of the drawbacks of the conventional method of nitrogen removal was the need for maintenance of specific pH conditions. While mild alkaline conditions (7–8) are appropriate for nitrification, a weakly acidic environment is preferred by denitrifiers (Lei et al. 2019). pH values closer to either 5 or 10 resulted in no change or increase in nitrogen removal due to the unsuitability of the strongly acidic or alkaline environment for the survival of bacteria (Zhang et al. 2019). However, simultaneous nitrification–denitrification creates, in a cyclic manner, pH conditions appropriate for the process as a whole. The acidity generated during nitrification is suitable for the denitrification process which in turn creates alkaline conditions appropriate for nitrification (Li et al. 2018b). Kim et al. (2005) reported that a pH value of 7 has a positive effect on simultaneous nitrification and denitrification ability of *Bacillus* strain. There are also available strains like *Pseudomonas putida* ZN1 (Zhang et al. 2019) which prefer pH 7 as optimum for processes aerobic denitrification, heterotrophic nitrification, and simultaneous nitrification- denitrification.

The use of heterotrophic nitrification-aerobic denitrification technology for real wastewater treatment is still in its early stages. This is mainly due to the reduced processing efficiency of potential strains. Fluctuations in salinity and nitrogen concentrations in real effluents also have a significant impact on the performance of these strains (Zhang et al. 2012; Gui et al. 2017). Therefore, it is urgent to identify strains capable of performing SND in hostile environments such as those with high concentrations of nitrogen and salt. He et al. (2019) isolated and identified *Pseudomonas mendocina* TJPU04 and examined its cell growth and yield. Results expressed that strain TJPU04 is effective in nitrogen removal from effluent under non-sterile conditions of high salt content and variable nitrogen concentrations. Chlorate is another inhibitor of cell growth and denitrification (Zhou et al. 2014). However, studies performed by Lei et al. (2019) using the strain *Ochrobactrum anthropic* LJ81 confirmed that the addition of chlorate only affects denitrification and not the nitrification process.

Different studies have employed the use of different organisms and successfully achieved simultaneous nitrification and denitrification. Lee et al. (2001) used a mixed methanotrophic culture in a batch reactor and reported complete nitrate removal within 10 h but ammonia removal at a slower rate. Hibiya et al. (2003) successfully and completely removed nitrogen and carbon components from domestic wastewater by simultaneous nitrification–denitrification in a membrane -aerated biofilm reactor using different bacteria distributed horizontally and vertically in biofilms fixed on hollow fiber membrane in a single reactor. Similarly, Qi et al. (2003) also reported an efficient SND process using aerobic granular sludge and controlling the amount of carbon in a sequencing batch reactor. Khardenavis et al. (2007) demonstrated the ability of *Diaphorobacter* for simultaneous nitrification and denitrification under aerobic conditions with 85–93% COD removal and 92–96% ammonia removal and suggested their application in the treatment of high-nitrogen-containing wastewaters. *Providencia rettgeri* exhibited the ability to heterotrophically nitrify and aerobically denitrify ammonium within 12–48 h under conditions of C/N 10, 30 °C, 120 rpm (Taylor et al. 2009). Compact suspended carrier biofilm reactor system was operated by Xia et al. (2010) at different C/N ratios (10:1, 5:1, and 3:1) and the whole process was able to achieve 83.3% effective nitrification–denitrification at C/N ratio 3:1.

Chen and Ni (2011) isolated three strains, *Achromobacter* sp. GAD3, *Comamonas* sp. GAD4 and *Agrobacterium* sp. LAD9, from landfill leachate system. Out of these, GAD4 was able to achieve the highest aerobic nitrification–denitrification rate of 0.381 mmol L^{-1} h^{-1}, followed by LAD9 (0.374 mmol L^{-1} h^{-1}) and GAD3 (0.346 mmol L^{-1} h^{-1}). Qiu et al. (2012) screened *Pseudomonas* sp. as an aerobic nitrifying-denitrifying bacterium from activated sludge with the capability to remove 94% of 70 mgL^{-1} NH_4^+-N and 90% of 50 mgL^{-1} NO_3^--N. *Alcaligenes faecalis* C16 identified by Liu et al. (2015) was found to have the ability to heterotrophically nitrify and aerobically denitrify in the presence of both nitrate and ammonium. High ammonium tolerance of the organism was associated with the use of citrate and acetate as carbon sources with a C/N ratio of 7 for acetate and 14 for citrate. Lei et al. (2016) identified heterotrophic *Zobellella taiwanensis* DN-7 for the conversion of nitrite, nitrate, and ammonium to N_2 as the primary end product and advocated it as a promising candidate for high-strength ammonium wastewater treatments.

Flat-panel air–cathode microbial fuel cell (FA-MFC) system using *Nitrosomonas* and *Nitratireductor* sp. was developed by Park et al. (2017) for treating domestic wastewater and complete removal of total nitrogen was achieved at a rate of 0.62 kg-Nm^{-3} d^{-1}. Zhang et al. (2019) performed nutrient removal by a *Pseudomonas putida* strain and accomplished 97.47% ammonium, 86.08% nitrate, and 71.57% nitrite removal by heterotrophic nitrification-aerobic denitrification. *Ochrobactrum anthropic* was found to remove sole and mixed nitrogen sources without accumulation of nitrite during the SND process wherein more than 80% of initial nitrogen was converted into gaseous nitrogen (Lei et al. 2019).

Disproportionate levels of nitrogenous pollutants in different ecological niches with different environmental conditions highlight the need for metabolic diversity and robustness among the bacterial community to achieve successful nitrogen removal from wastewaters. So far, the identification and performance of SND capable microorganisms are quite promising, especially in the most prevalent conditions of variable COD levels. However, it is necessary to further evaluate and establish their performance under in situ stress conditions of heavy metals, salt, and the presence of other microflora.

Phosphorous accumulating microorganisms

Excessive discharge of phosphorous into water bodies leads to eutrophication and other perilous effects associated with it. Enhanced biological phosphorus removal (EBPR) is the most effective and sustainable method to get rid of phosphorus from wastewaters (Nielsen et al. 2019). It employs the phosphate accumulating organisms (PAO) which follow an alternative aerobic-anaerobic cycle (Liu et al. 2018). During the anaerobic phase, PAOs hydrolyze the intracellular phosphate and glycogen reserves for energy generation. This energy is utilized for the uptake and storage of volatile fatty acids in the form of polyhydroxyalkanoates (PHAs). PHA synthesis is accompanied by the extracellular release of phosphate ions. Uptake of organic matter gives a competitive advantage to PAOs. During the aerobic phase, these organisms degrade the accumulated PHAs as a source of energy and use a part of this energy to accumulate more phosphorous into their cells than that released during the anaerobic phase and store it as polyphosphate, thus removing phosphorus from wastewaters (Shen and Zhou 2016). Diagrammatically the process is depicted in Fig. 2. Microbial genera capable of EBPR include *Microlunatus, Tessaracoccus* (Stokholm-Bjerregaard et al. 2017), *Tetrasphaera* (Marques et al. 2018), *Candidatus* Accumulibacter (Rubio-Rincon et al. 2019) and *Dechloromonas* (Anuar et al. 2020) along with *Pseudomonas stutzeri* (Li et al. 2015), *Enterobacter cloacae* (Wan et al. 2017), *Arthrobacter* sp. (Zhang et al. 2020). *Candidatus* Accumulibacter phosphatis is considered important for phosphorous removal since it has been consistently found in wastewaters (Marques et al. 2018; Nielsen et al. 2019). It belongs to the family *Rhodocyclacea*

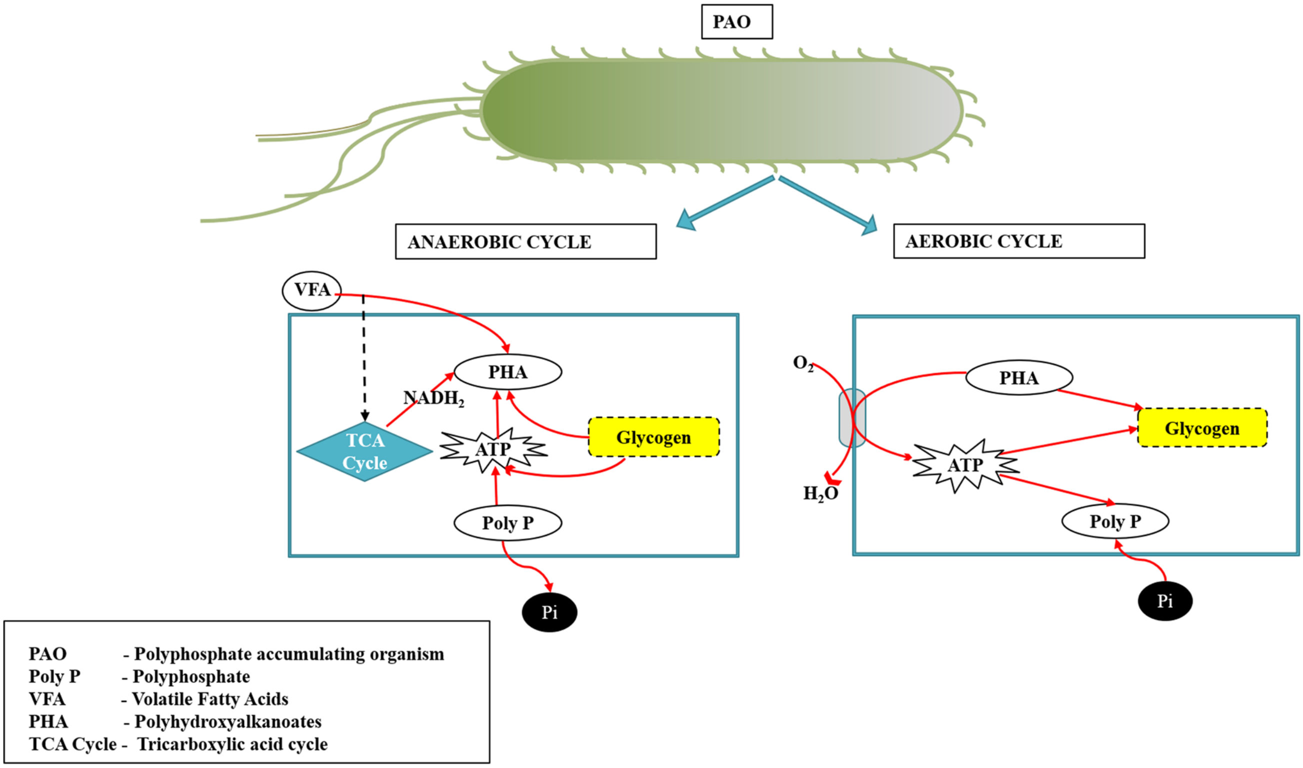

Fig. 2 Biological route of phosphorous removal

of class *Beta Proteobacteria* (Dorofeev et al. 2019). Activated sludge from wastewater treatment plants is the most well-known habitat of *Candidatus* Accumulibacter phosphatis besides sediments of estuaries and freshwater bodies (Dorofeev et al. 2020).

Process of phosphorous uptake is catalyzed by the activity of the enzyme polyphosphate-adenosine diphosphate phosphotransferase, also known as polyphosphate kinase (ppk), encoded by the *ppk* gene (Li et al. 2015). It helps in the elongation of the poly-P chain (Achbergerova and Nahalka 2011). PAOs chiefly prefer volatile fatty acids (acetate and propionate) for the synthesis of intracellular polyhydroxyalkanoates (PHAs). Their activity gets augmented at a pH between 6.5–7.5 and temperatures between 15–30 °C (Nancharaiah et al. 2016). Recently, Zhang et al. (2020) tested different conditions of pH and temperature and achieved above 99% phosphorus removal by *Arthrobacter* sp. HHEP5 at temperatures between 18–28 °C and pH 5.5–8.5.

PAOs have a higher capacity for intracellular phosphorus accumulation than the non-phosphorous accumulating heterotrophic bacteria (Dorofeev et al. 2020). They may be used in laboratory-scale reactors and full-scale wastewater treatment plants forming a dominant part of the bacterial community involved in the removal of phosphorus (Nancharaiah et al. 2016). However, low phosphorus removal efficiencies have been reported in PAOs identified so far. Therefore it is important to focus more on the isolation and identification of strains of PAOs with higher efficiencies since most species of known PAOs are significantly rare.

DNPAOs or the denitrifying phosphate-accumulating organisms are a subgroup of PAOs. These microorganisms are metabolically similar to PAOs (Bassin et al. 2012). Most significant DNPAOs belong to class *Beta Proteobacteria* and are *Dechloromonas* and *Zoogloea* (Kondo et al. 2009). Whereas PAOs can only use oxygen as an electron acceptor for respiration, DNPAOs can also use nitrite or nitrate (Yuan and Oleszkiewicz 2010) to absorb phosphates by degrading PHAs (Zhang et al. 2010). However, the affinity of PAOs towards oxygen is higher and phosphorous uptake faster than the DNPAOs (Salehi et al. 2019). Even then, the chemical oxidation demand is a limiting factor for PAOs and is overcome by the process of simultaneous nitrification–denitrification and phosphorous removal (SNDPR) that can achieve the removal of both nitrogen and phosphorus at low carbon levels in wastewaters (Bassin et al. 2012).

Simultaneous Removal Of Nitrogen And Phosphorus

The discovery of microorganisms capable of performing both simultaneous nitrification–denitrification and phosphorous removal (SNDPR) makes single-stage removal of nitrogen and phosphorous an attractive strategy (He et al. 2016a). So far, only a few microbial species with this potential have been cited (Table 2). These are mostly found in aquaculture environments and employ the same set of enzymes and genes as those involved in the individual processes of EBPR and SND (Zhang et al. 2020). A model for the mechanism of SNDPR is illustrated in Fig. 3. Under heterotrophic aerobic conditions, organisms capable of SNDPR are concomitantly able to convert nitrogen compounds (mainly ammonium and nitrate) and uptake phosphorous intracellularly. While phosphorous gets accumulated in the form of polyphosphate, ammonium and nitrate undergo a series of enzyme-catalyzed steps resulting in the formation of dinitrogen. Part of this nitrogen is used up by the organism for its growth and the rest escapes into the environment.

SNDPR strains perform stable nitrogen and phosphorus removal at a low C/N ratio (Chen et al. 2020). The effective temperature is within the mesophilic range and pH between 7 and 8 (Wang et al. 2018; Salehi et al. 2019). Major advantages associated with the SNDPR process are lower COD demand, lesser sludge production, and low aeration cost (Wang et al. 2016). The potential of SNDPR organisms promises to solve the problem of bacterial changes to remove both nitrogen and phosphorus from wastewaters (Wan et al. 2017). Also, their success rate ensures a cost-effective and sustainable strategy for wastewater treatment.

Role of SNDPR organisms in bioremediation

The identification of novel bacteria with a unified potential of SND and EBPR has opened ways for the simultaneous treatment of accumulated nutrients in industrial and domestic wastewaters, eutrophic lakes, and aquaculture systems. However, the numbers and efficiency of these bacteria known so far are extremely low and their applicability is still very limited. Yang et al. (2010) performed simultaneous removal of nitrogen and phosphorus in a sequencing batch moving bed membrane bioreactor. COD/N ratio was kept between 5.6–12.9 and 93.5% carbon and 82.6% nitrogen removal was achieved. Also, an increase in time duration by 2 h resulted in 84.1% total phosphorus removal. It was also observed that dissolved oxygen (3 mg L^{-1}) in the aerobic phase was a major factor contributing to the simultaneous removal of nitrogen and phosphorus.

Over 13 months, synthetic wastewater was treated under alternating anaerobic and aerobic conditions in a lab-scale sequencing batch reactor sown with granular sludge. The loading rates of organic carbon, nitrogen, and phosphorus were 2.7 g $CODL^{-1}$ d^{-1}, 0.43 g NL^{-1} d^{-1}, and 0.06 g PL^{-1} d^{-1} respectively and removal efficiency of 68% total COD, 86% total nitrogen, and 74% total phosphorous were obtained indicating that granular sludge facilitated the

Table 2 Microbial spp involveld in simultaneous removal of nitrogen and phosphorus

Bacterial strain	Reactor	Isolation site	Country	Type of wastewater	Nitrogen removal efficiency (%)	Phosphorus removal efficiency (%)	References
Auxenochlorella protothecoides UMN280	–	Saint Paul, Minnesota	United States	Muncipal wastewater	59%	81%	Zhou et al. (2012)
Pseudomonas stutzeri YG-24	–	Beijing	China	Domestic wastewater	80%	51%	Li et al. (2015)
Bacillus cereus GS-5	–	Bhubaneswar, Odisha	India	Domestic wastewater	–	–	Rout et al. (2017)
Enterobacter clocae HW-15	–	Beijing	China	Domestic wastewater	96.16	73%	Wan et al. (2017)
Pseudomonas denitrificans ISTOD1	–	JNU, New Delhi	India	Domestic wastewater	71%	93%	Medhi and Thakur (2018)
Accumulibacter sp	Sequencing batch reactor (SBR)	Queensland	Australia	Abattoir wastewater	93%	89%,	Yilmaz et al. (2008)
Bacillus origin MCC0008, MCC2059, MCC2071	Glass and Scaled up Bioreactor	Keshtopur, Kolkata	India	Domestic wastewater	94%	68%	Saha et al. (2018)
Cadidatus Competibacter, Cadidatus Accumlibacter, Tetrasphaera	Partial nitrification endogenous denitrification and phosphorus removal (PNEDPR)	Beijing	China	Muncipal wastewater	86.8%	90.9%	Zhao et al. (2019)
Pseudorhodobacter	Sequencing batch biofilm reactor (N-SBBR)	Tianjin	China	Domestic wastewater	75.47%	65.87%	Chao et al. (2020)
Arthrobacter sp. HHEP5	–	–	–	Domestic wastewater	95%	99%	Zhang et al. (2020)

SNDPR process (Yilmaz et al. 2008). Similarly, Kishida et al. (2009), Lochmatter et al. (2013), and Wei et al. (2014) also successfully used aerobic granular sludge systems for simultaneously removing nitrogen and phosphorus from wastewaters.

Auxenochlorella protothecoides, a microalgal strain was examined for nutrient removal and showed 59% removal of total nitrogen and 81% total phosphorus removal from municipal wastewater in six days (Zhou et al. 2012). Rasoul-Amini et al. (2014) used batch cultures of five microalgae strains for removal of NO_3-N and orthophosphate (PO_4^{3}-P) from wastewater. It was observed that *Chlorella* sp. (YG01) achieved a higher N removal (84.11%) whereas strains *Chlamydomonas* sp. (YG05) and *Chlamydomonas* sp. (YG04) achieved higher P uptake (100%) from wastewater. Similarly, a microalgae-bacteria consortium was prepared by Delgadillo-Mirquez et al. (2011) for the removal of nutrients (nitrogen and phosphorus) and achieved an average of 72–83% nitrogen and 100% phosphorus removal, besides converting these nutrients into biomass. Therefore, even microalgae have been found helpful in the removal of nutrients from wastewater.

Phosphate accumulating bacteria *Pseudomonas stutzeri* YG-24 (Li et al. 2015) and *Enterobacter cloacae* HW-15 (Wan et al. 2017) have presented a great ability of nitrogen and phosphorus removal from real wastewaters. *Achromobacter* and *Agrobacterium* also possess a versatile genomic potential for concurrent removal of nitrogen and phosphorous in a single unit system during the treatment of wastewater (Liu et al. 2018). Rout et al. (2017) used a *Bacillus cereus* strain and reported efficient simultaneous removal of ammonium, nitrate, nitrite, and phosphate from domestic wastewater with average rates of 2.62, 2.69, 1.16 and 0.42 mg L^{-1} h^{-1} respectively under aerobic conditions. Zhang et al. (2020) isolated *Arthrobacter* sp. HHEP5 as a novel PAO from a mariculture environment and demonstrated its ability in mariculture and domestic wastewater treatment with 99% phosphorus and 95% nitrogen removal

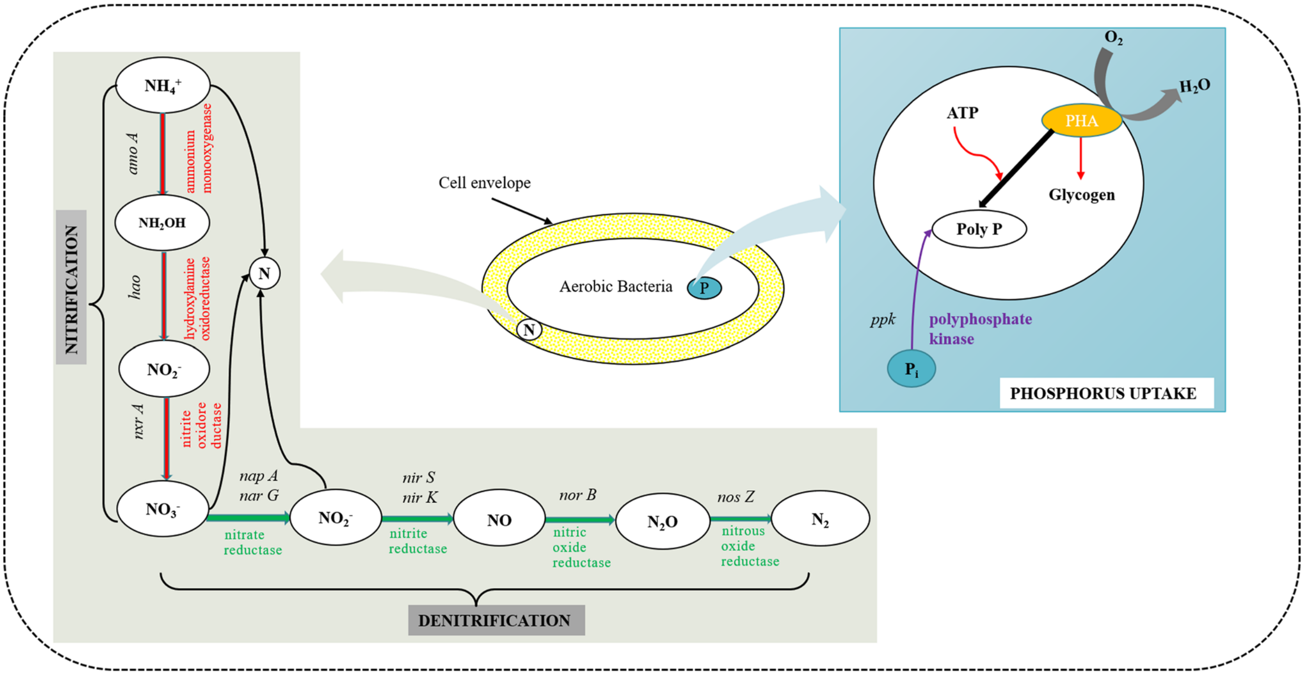

Fig. 3 A model for the simultaneous nitrification–denitrification and phosphorous removal (SNDPR) in aerobic microorganisms

in both the environments. They also reported that varying the environmental factors (pH, temperature, C/N ratio, P/N ratio, salinity, and rpm) improved the removal efficiencies of HHEP5.

The application of a microbial consortium is one of the fastest and energy-efficient technologies to date. Three different strains of *Bacillus* (MCC 0008, MCC 2059, MCC 2071) were employed as a consortium at ambient temperature in a biofilm reactor and showed simultaneous sequestration of 94% nitrate, 68% phosphorus, 93% COD, 97% BOD and 73% total organic carbon (Saha et al. 2018). Zhao et al. (2019) appraised a novel system of nitrogen and phosphorus removal that could aid the removal of nitrogen deprived of carbon wherein *Candidatus* Competibacter ensured 86.8% nitrogen removal and *Candidatus* Accumulibacter phosphatis and *Tetrasphaera* achieved 90.9% phosphorus removal. Rout et al. (2018) accomplished highly effective removal of nitrogen and phosphorus at the same time by immobilizing *Bacillus cereus* GS-5 strain in an inventive single unit multi-layered packed bed bioreactor which also included some packing parts containing a mixture of solid organic wastes and dolochar. The reactor was operated for 70 days using both synthetic and domestic wastewater and was able to achieve 87–93% removal of NH_4^+-N, 69–88% NO_3-N removal, 84–100% PO_4^{3-}-P removal and also 69.8–92% reduction of COD.

The bioremediation of nitrogen and phosphorous pollutants is an economical and sustainable approach in comparison to other physical and chemical methods. However, the focus of most studies until now has been the microbial analysis of this system, and its adaptability and efficacy are quite unsatisfactory. The overall process requirements and time management become a lot simpler but performance would depend on the ability of microorganisms to increase removal efficiencies and overcome natural environmental conditions which bring in the need to explore newer strains with enhanced abilities for simultaneous removal of nitrogen and phosphorous under aerobic conditions using cost-effective substrates.

Immobilization of biological components for removal of inorganic contaminants from water

Immobilization technology is receiving a lot of attention in treating wastewaters Immobilization involves the restricted movement of cells by natural or artificial means. Some of the most common immobilization techniques include covalent coupling, affinity immobilization, capture behind the semi-permeable membrane, entrapment in polymers, and adsorption (Xie et al. 2020). Basic requirements for immobilized systems such as retention of viability, high cell density, and low leakage of cells from a matrix must be fulfilled for successful water treatment. Apart from these, an ideal matrix for immobilization should be chosen which is resistant to disruption, non-toxic, and able to retain biomass. Studies have stated that immobilized cells can increase the removal efficiency of nutrients by more than 60% (Bouabidi et al. 2019). Compared to free cells, immobilization of cells offers several great advantages in bioremediation such as increased conversion rates due to higher cell loading densities, continuous supply of nutrients without any competition with other organisms (De-Bashan and Bashan 2004), protection against environmental stress, no need for cell suppression (De-Bashan and Bashan 2010) and elimination of washout possibilities even at high dilution rates hence allowing a continuous process.

Different studies report the immobilization and co-immobilization of organisms performing specific functions for the treatment of waters containing high concentrations of nitrogen and phosphorous (Shen et al. 2017). For example, co-immobilization of nitrifiers and denitrifiers allows the two separate processes of nitrification and denitrification to be conducted as if single staged. In this direction, Santos et al. (1996) prepared a simultaneous or one reactor system using a bubble column reactor in which *Nitrosomonas europaea* and *Pseudomonas denitrificans* were co-immobilized in a double layer of (25% v/v) alginate carrageenan beads and successfully achieved a high nitrogen removal rate (5.1 mmol N m^{-1}gel s^{-1}). Similarly, Hill and Khan (2008) conducted a bench-scale study using two reactor systems to remove ammonia from sludge digester. One system comprised of immobilized nitrifiers and the other consisted of both co-immobilized denitrifiers and nitrifiers. It was seen that the co-immobilized cell reactor removed 8.5% more total nitrogen than the cell reactor with individually immobilized nitrifiers. Large voids caused due to N_2 gas in several co-immobilized beads samples provided evidence of denitrifying activity.

Immobilization of microorganisms involved in nitrogen and phosphorous removal has also been carried out using different organic and inorganic carrier materials with a high success rate. *Rhodobacter sphaeroids* was immobilized on a porous ceramic plate for denitrification of sewage water and a high nitrate removal rate of 5.04 kg m^{-3} $d^{-1}$was obtained (Nagadomi et al. 2000). Phosphate accumulating strain *Pseudomonas stutzeri* YG-24 was isolated from Taihu Lake, China, and immobilized in polyvinyl alcohol -sodium alginate beads. Even though both the free and immobilized cells were able to remove 97% to 100% phosphorus from synthetic wastewater, the removal process was faster using immobilized cells (8 h) than the free cells (12 h) (Li et al. 2012). Similarly, Wang et al. (2013) isolated and immobilized denitrifying *Pseudomonas* using polyvinyl-alcohol and reported that immobilized pellets had a significantly higher nitrate removal rate than the non-immobilized bacteria. Complete nitrate removal was achieved when pellets were reused in 12 h.

Ma et al. (2015) used three different supports, sodium alginate beads, mycelial pellets, and polyurethane foam cubes for immobilization of *Pseudomonas stutzeri* and achieved excellent nitrogen removal. Immobilization in sodium alginate beads had 57.25% nitrogen removal as compared to 29.7% by free cells. However, Tang et al. (2020) used gel beads of sodium alginate, graphene oxide, and polyvinyl-alcohol as a carrier material for *Pseudomonas fluorescens* Z03 to improve nitrogen removal efficiency at very low temperatures of 6–8 °C and found graphene oxide beads to be most effective with a removal efficiency of 96.38–97.24% and 98.82–99.12% for NH_4^+−N and NO_3^-−N respectively.

Chen et al. (2015a) incorporated biomass entrapped in bio-plates having cellulose triacetate structure into a reactor basin for carrying out simultaneous nitrification and denitrification and observed that bio-carriers were able to achieve 74% total nitrogen removal in domestic effluent without any supplemental carbon or alkalinity. This demonstrated the immobilization of biomass to be a very efficient mechanism for wastewater treatment plants. Simultaneous removal of nitrogen and phosphorus was achieved by Yin et al. (2015) using a sequencing batch reactor-biofilm system with an average removal of 95% COD, 94% total nitrogen, and 97% total phosphorus over 3 months. Li et al. (2016) used a bio-trickling filter packed with biochar from porous palm residues and inoculated with microbial consortia for treatment of nitrogen and phosphorus-rich wastewater and achieved 80% ammonium and 68% phosphorus removal. *Acinetobacter* sp. TX5 was immobilized on the spent *Hypsizygus marmoreus* substrate for simultaneous nitrification and denitrification of raw piggery wastewater (Yang et al. 2018). In a batch system, the immobilized *Acinetobacter* sp. TX5 achieved 89% NH_4^+−N removal in 8 h; and in a continuous system it achieved 94–95% NH_4^+-N, 73–93% total nitrogen and 54–82% COD removal in 96 h.

Katam and Bhattacharyya (2019) compared the use of immobilized microalgae and suspended activated sludge to suspended co-culture for nitrogen and phosphorous removal and concluded that immobilization of algae in alginate beads was synergistically better than suspended co-culture. Nancharaiah and Sarvajith (2019) and He et al. (2020) have promoted the use of aerobic granular sludge composed of self-immobilized microbial groups to achieve simultaneous nitrogen and phosphorus removal (SNDPR) from industrial and domestic wastewaters. Therefore the performance of microorganisms involved in nutrient removal from wastewaters has been enhanced using different immobilization matrices. However, the nature of the immobilization material can further influence the removal process which may also depend on the type of microbial species, wastewater, and environmental conditions.

Conclusion

The bioremediation of polluted waters is imperative to maintain water quality. Among the diverse range of organisms that can participate in the biological removal of inorganic pollutants from wastewaters, the potential of bacteria with the ability for simultaneous heterotrophic nitrification aerobic denitrification is far-reaching. Faster growth, simpler process requirements, conversion from ammonium to nitrogen, and the ability to perform under a variety of environmental conditions, places them ahead of other organisms with similar functions. Further, identification of novel phosphate accumulating bacteria that can remove both phosphorous and nitrogen has opened ways for the simultaneous treatment of accumulated nutrients. The success of SNDPR organisms ensures an economical and sustainable strategy and promises to overcome problems encountered in wastewater treatment such as the need for a shift in the microbial community due to different process requirements. However, studies about their adaptability and applicability are still very limited. Performance would depend on the ability of these microorganisms to increase removal efficiencies and overcome natural environmental conditions. The use of immobilized microorganisms over free cells can further enhance the removal rates. Therefore, it is urgent to explore newer strains with enhanced abilities for simultaneous removal of nitrogen and phosphorous using cost-effective and environmentally responsive substrates for the total eradication of contaminants from wastewater.

Future prospects

The dangers of nutrient pollution need to be addressed to find long-term, economical solutions. Although the discovery of aerobic heterotrophic bacteria that can simultaneously remediate both nitrogen and phosphorous in a single unit is a boon to a great extent, there are still deficiencies that need to be overcome to achieve complete removal. There is a persistent requirement of extensively researched efficient strains that can withstand different environmental conditions to treat real wastewaters. The role of various genes and variability in metabolic pathways followed in aerobic organisms also need further understanding. Knowledge of the ecological interactions of these organisms with other microbiota can assist in the development of efficient consortia which can be applied to treat several other contaminants as well. There is an increasing need to focus on improving the performance and applicability of these organisms and the use of various natural carbon sources to reduce process costs. Thus, till the time these gaps are filled, the process of simultaneous nitrification–denitrification by phosphate accumulating microorganisms remains a partially fulfilled task in the treatment of contaminated waters.

References

Abbassi R, Yadav AK, Huang S, Jaffé PR (2014) Laboratory study of nitrification, denitrification and anammox processes in membrane bioreactors considering periodic aeration. J Environ Manage 142:53–59

Abdel-Raouf N, Al-Homaidan AA, Ibraheem IB (2012) Microalgae and wastewater treatment. Saudi J Biol Sci 19:257–275

Achbergerova L, Nahalka J (2011) Polyphosphate - an ancient energy source and active 639 metabolic regulator. Microb Cell Fact 10:63

Ahlström H, Cornell SE (2018) Governance, polycentricity and the global nitrogen and phosphorus cycles. Environ Sci Policy 79:54–65

Ahmed MB, Zhou JL, Ngo HH, Guo W, Thomaidis NS, Xu J (2017) Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: a critical review. J Hazard Mater 323:274–298

Anjaneyulu Y, Chary NS, Raj DS (2005) Decolourization of industrial effluents–available methods and emerging technologies—a review. Rev Environ Sci Bio 4:245–273

Anuar AN, Ab Halim MH, Rosman NH, Othman I, Harun H, Basri HF, van Loosdrecht M (2020) Microbial identification and extracellular polymeric substances characterization of aerobic granules developed in treating rubber processing wastewater. In: Zakaria ZA, Boopathy R, Dib JR (eds) Valorisation of agro-industrial residues–Volume I: Biological Approaches. Springer, Cham, pp 257–286

Bai H, Liao S, Wang A, Huang J, Shu W, Ye J (2019) High-efficiency inorganic nitrogen removal by newly isolated *Pannonibacter phragmitetus* B1. Bioresour Technol 271:91–99

Barman P, Bandyopadhyay P, Kati A, Paul T, Mandal AK, Mondal KC, Mohapatra PKD (2018) Characterization and strain improvement of aerobic denitrifying EPS producing bacterium *Bacillus cereus* PB88 for shrimp water quality management. Waste Biomass Valoriz 9:1319–1330

Bassin JP, Kleerebezem R, Dezotti M, Van Loosdrecht MC (2012) Simultaneous nitrogen and phosphate removal in aerobic granular sludge reactors operated at different temperatures. Water Res 46:3805–3816

Bouabidi ZB, El-Naas MH, Zhang Z (2019) Immobilization of microbial cells for the biotreatment of wastewater: a review. Environ Chem Lett 17:241–257

Bratby J (2016) Coagulation and flocculation in water and wastewater treatment. IWA Publishing, London

Cai W, Huang W, Lei Z, Zhang Z, Lee DJ, Adachi Y (2019) Granulation of activated sludge using butyrate and valerate as additional carbon source and granular phosphorus removal capacity during wastewater treatment. Bioresour Technol 282:269–274

Carolin CF, Kumar PS, Saravanan A, Joshiba GJ, Naushad M (2017) Efficient techniques for the removal of toxic heavy metals from aquatic environment: a review. J Environ Chem Eng 5:2782–2799

Chao C, Zhao Y, Keskar J, Ji M, Wang Z, Li X (2020) Simultaneous removal of COD, nitrogen and phosphorus and the tridimensional microbial response in a sequencing batch biofilm reactor: with varying C/N/P ratios. Biochem Eng J 154:107–215

Chen G (2004) Electrochemical technologies in wastewater treatment. Sep Purif Technol 38:11–41

Chen HY, Andy Hong PK, Yang PY, Kwang Ng K, Yang SF, Lee CH, Lin CF (2015a) A pilot study on suspended activated sludge process augmented with immobilized biomass for simultaneous nitrification and denitrification. J Water Reuse Desalination 5:157–165

Chen J, Strous M (2013) Denitrification and aerobic respiration, hybrid electron transport chains and co-evolution. Biochi Biophys Acta 1827:136–144

Chen J, Zheng J, Li Y, Hao HH, Chen JM (2015b) Characteristics of a novel thermophilic heterotrophic bacterium, *Anoxybacillus contaminans* HA, for nitrification–aerobic denitrification. Appl Microbial Biotechnol 99:10695–10702

Chen Q, Ni J (2011) Heterotrophic nitrification–aerobic denitrification by novel isolated bacteria. J Ind Microbiol Biot 38:1305–1310

Chen Y, Li S, Lu Y, Zhu G, Cheng H (2020) Simultaneous nitrification, denitrification and phosphorus removal (SNDPR) at low atmosphere pressure. Biochem Eng J 160:107629

Chiu YC, Lee LL, Chang CN, Chao AC (2007) Control of carbon and ammonium ratio for simultaneous nitrification and denitrification in a sequencing batch bioreactor. Int Biodeter Biodegr 59:1–7

Cotto I, Dai Z, Huo L, Anderson CL, Vilardi KJ, Ijaz U, Bailey E (2020) Long solids retention times and attached growth phase favor prevalence of comammox bacteria in nitrogen removal systems. Water Res 169:115268

Crini G, Lichtfouse E (2019) Advantages and disadvantages of techniques used for wastewater treatment. Environ Chem Lett 17:145–155

Daims H, Lebedeva EV, Pjevac P, Han P, Herbold C, Albertsen M, Kirkegaard RH (2015) Complete nitrification by *Nitrospira* bacteria. Nature 528:504–509

De-Bashan LE, Bashan Y (2004) Recent advances in removing phosphorus from wastewater and its future use as fertilizer (1997–2003). Water Res 38:4222–4246

De-Bashan LE, Bashan Y (2010) Immobilized microalgae for removing pollutants: review of practical aspects. Bioresour Technol 101:1611–1627

Delgadillo-Mirquez L, Lopes F, Taidi B, Pareau D (2011) Nitrogen and phosphate removal from wastewater with a mixed microalgae and bacteria culture. Biotechnol Rep 11:18–26

Dorofeev AG, Nikolaev YA, Mardanov AV, Pimenov NV (2019) Cyclic metabolism as a mode of microbial existence. Microbiology 88:402–415

Dorofeev AG, Nikolaev YA, Mardanov AV, Pimenov NV (2020) Role of phosphate-accumulating bacteria in biological phosphorus removal from wastewater. Appl Biochem Microbiol 56:1–14

Elser JJ (2012) Phosphorus: a limiting nutrient for humanity? Curr Opin Biotechnol 23:833–838

Fabro AYR, Ávila JGP, Alberich MVE, Sansores SAC, Camargo-Valero MA (2015) Spatial distribution of nitrate health risk associated with groundwater use as drinking water in Merida, Mexico. Appl Geogr 65:49–57

Guadie A, Xia S, Zhang Z, Guo W, Ngo HH, Hermanowicz SW (2013) Simultaneous removal of phosphorus and nitrogen from sewage using a novel combo system of fluidized bed reactor–membrane bioreactor (FBR–MBR). Bioresour Technol 149:276–285

Gui M, Chen Q, Ni J (2017) Effect of NaCl on aerobic denitrification by strain *Achromobacter* sp. GAD-3. Appl Microbiol Biot 101:5139–5147

Guo J, Zhang L, Chen W, Ma F, Liu H, Tian Y (2013) The regulation and control strategies of a sequencing batch reactor for simultaneous nitrification and denitrification at different temperatures. Bioresour Technol 133:59–67

Guo LJ, Zhao B, An Q, Tian M (2016) Characteristics of a novel aerobic denitrifying bacterium, *Enterobacter cloacae* strain HNR. Appl Biochem Biotechnol 178:947–959

He Q, Song J, Zhang W, Gao S, Wang H, Yu J (2020) Enhanced simultaneous nitrification, denitrification and phosphorus removal through mixed carbon source by aerobic granular sludge. J Hazard Mater 382:121043

He Q, Zhang S, Zou Z, Zheng LA, Wang H (2016a) Unraveling characteristics of simultaneous nitrification, denitrification and phosphorus removal (SNDPR) in an aerobic granular sequencing batch reactor. Bioresour Technol 220:651–655

He T, Li Z, Sun Q, Xu Y, Ye Q (2016b) Heterotrophic nitrification and aerobic denitrification by *Pseudomonas tolaasii*Y-11 without nitrite accumulation during nitrogen conversion. Bioresour Technol 200:493–499

He T, Li Z, Xie D, Sun Q, Xu Y, Ye Q, Ni J (2018) Simultaneous nitrification and denitrification with different mixed nitrogen loads by a hypothermia aerobic bacterium. Biodegradation 29:159–170

He X, Sun Q, Xu T, Dai M, Wei D (2019) Removal of nitrogen by heterotrophic nitrification–aerobic denitrification of a novel halotolerant bacterium *Pseudomonas mendocina* TJPU04. Bioproc Biosyst Eng 42(853–866):2

Hibiya K, Terada A, Tsuneda S, Hirata A (2003) Simultaneous nitrification and denitrification by controlling vertical and horizontal microenvironment in a membrane-aerated biofilm reactor. J Biotechnol 100:23–32

Hill CB, Khan E (2008) A comparative study of immobilized nitrifying and co-immobilized nitrifying and denitrifying bacteria for ammonia removal from sludge digester supernatant. Water Air Soil Poll 195:23

Hocaoglu SM, Insel G, Cokgor EU, Orhon D (2011) Effect of low dissolved oxygen on simultaneous nitrification and denitrification in a membrane bioreactor treating black water. Bioresour Technol 102:4333–4340

Hou L, Zheng Y, Liu M, Gong J, Zhang X, Yin G, You L (2013) Anaerobic ammonium oxidation (anammox) bacterial diversity, abundance, and activity in marsh sediments of the Yangtze Estuary. J Geophys Res Biogeosci 118:1237–1246

Huang G, Ou L, Pan F, Wang Y, Fan G, Liu G, Wang W (2017) Isolation of a novel heterotrophic nitrification–aerobic denitrification bacterium *Serratia marcescens* CL1502 from deep-sea sediment. Environ Eng Sci 34:453–459

Jin R, Liu T, Liu G, Zhou J, Huang J, Wang A (2015) Simultaneous heterotrophic nitrification and aerobic denitrification by the marine origin bacterium *Pseudomonas* sp. ADN-42. Appl Biochem Biotechnol 175:2000–2011

Joo HS, Hirai M, Shoda M (2005) Characteristics of ammonium removal by heterotrophic nitrification-aerobic denitrification by *Alcaligenes faecalis* No. 4. J Biosci Bioeng 100:184–191

Katam K, Bhattacharyya D (2019) Simultaneous treatment of domestic wastewater and bio-lipid synthesis using immobilized and suspended cultures of microalgae and activated sludge. J Ind Eng Chem 69:295–303

Khalaf MN (2016) Green polymers and environmental pollution control. CRC Press, Boca Raton

Khardenavis AA, Kapley A, Purohit HJ (2007) Simultaneous nitrification and denitrification by diverse *Diaphorobacter* sp. Appl Microbiol Biot 77:403

Kim JK, Park KJ, Cho KS, Nam SW, Park TJ, Bajpai R (2005) Aerobic nitrification–denitrification by heterotrophic *Bacillus* strains. Bioresour Technol 96:1897–1906

Kishida N, Tsuneda S, Kim JH, Sudo R (2009) Simultaneous nitrogen and phosphorus removal from high-strength industrial wastewater using aerobic granular sludge. Environ Eng 135:153–158

Kondo T, Tsuneda S, Ebie Y, Inamori Y, Xu K (2009) Characterization of the microbial community in the anaerobic/oxic/anoxic process combined with sludge ozonation and phosphorus adsorption. J Water Environ Technol 7:155–162

Lakha S, Shannon KE, Henderson SL, Goyer C, Trevors JT, Zebarth BJ, Burton DL (2009) Effect of pH and temperature on denitrification gene expression and activity in *Pseudomonas mandelii*. Appl Environ Microbiol 75:3903–3911

Lan CJ, Kumar M, Wang CC, Lin JG (2011) Development of simultaneous partial nitrification, anammox and denitrification (SNAD) process in a sequential batch reactor. Bioresour Technol 102:5514–5519

Lawson CE, Lücker S (2018) Complete ammonia oxidation: an important control on nitrification in engineered ecosystems? Curr Opin Biotechnol 50:158–165

Lee CG, Fletcher TD, Sun G (2009) Nitrogen removal in constructed wetland systems. Eng Life Sci 9:11–22

Lee HJ, Bae JH, Cho KM (2001) Simultaneous nitrification and denitrification in a mixed methanotrophic culture. Biotechnol Lett 23:935–941

Lei X, Jia Y, Chen Y, Hu Y (2019) Simultaneous nitrification and denitrification without nitrite accumulation by a novel isolated *Ochrobactrum anthropic* LJ81. Bioresour Technol 272:442–450

Lei Y, Wang Y, Liu H, Xi C, Song L (2016) A novel heterotrophic nitrifying and aerobic denitrifying bacterium, *Zobellellataiwanensis* DN-7, can remove high-strength ammonium. Appl Microbiol Biotechnol 100:4219–4229

Li C, Yang J, Wang X, Wang E, Li B, He R, Yuan H (2015) Removal of nitrogen by heterotrophic nitrification–aerobic denitrification of a phosphate accumulating bacterium *Pseudomonas stutzeri* YG-24. Bioresour Technol 182:18–25

Li HF, Li BZ, Wang ET, Yang JS, Yuan HL (2012) Removal of low concentration of phosphorus from solution by free and immobilized cells of *Pseudomonas stutzeri* YG-24. Desalination 286:242–247

Li L, Dong Y, Qian G, Hu X, Ye L (2018a) Performance and microbial community analysis of bio-electrocoagulation on simultaneous nitrification and denitrification in submerged membrane bioreactor at limited dissolved oxygen. Bioresour Technol 258:168–176

Li W, Loyola-Licea C, Crowley DE, Ahmad Z (2016) Performance of a two-phase biotrickling filter packed with biochar chips for treatment of wastewater containing high nitrogen and phosphorus concentrations. Process Saf Environ Prot 102:150–158

Li Y, Chapman SJ, Nicol GW, Yao H (2018b) Nitrification and nitrifiers in acidic soils. Soil Biol Biochem 116:290–301

Limpiyakorn T, Sonthiphand P, Rongsayamanont C, Polprasert C (2011) Abundancemof *amoA*genes of ammonia-oxidizing archaea and bacteria in activated sludge of full-scale wastewater treatment plants. BioresourTechnol 102:3694–3701

Liu H, Yang Y, Sun H, Zhao L, Liu Y (2018) Effect of tetracycline on microbial community structure associated with enhanced biological N&P removal in sequencing batch reactor. Bioresour Technol 256:414–420

Liu Y, Wang Y, Li Y, An H, Lv Y (2015) Nitrogen removal characteristics of heterotrophic nitrification-aerobic denitrification by *Alcaligenes faecalis* C16. Chin J Chem Eng 23:827–834

Lochmatter S, Gonzalez-Gil G, Holliger C (2013) Optimized aeration strategies for nitrogen and phosphorus removal with aerobic granular sludge. Water Res 47:6187–6197

Lockhart KM, King AM, Harter T (2013) Identifying sources of groundwater nitrate contamination in a large alluvial groundwater basin with highly diversified intensive agricultural production. J Contam Hydrol 151:140–154

Ma F, Sun Y, Li A, Zhang X, Yang J (2015) Activation of accumulated nitrite reduction by immobilized *Pseudomonas stutzeri* T13 during aerobic denitrification. Bioresour Technol 187:30–36

Marques R, Ribera-Guardia A, Santos J, Carvalho G, Reis MA, Pijuan M, Oehmen A (2018) Denitrifying capabilities of *Tetrasphaera* and their contribution towards nitrous oxide production in enhanced biological phosphorus removal processes. Water Res 137:262–272

Matamoros V, Gutiérrez R, Ferrer I, García J, Bayona JM (2015) Capability of microalgae-based wastewater treatment systems to remove emerging organic contaminants: a pilot-scale study. J Hazard Mater 288:34–42

Medhi K, Singhal A, Chauhan DK, Thakur IS (2017) Investigating the nitrification and denitrification kinetics under aerobic and anaerobic conditions by *Paracoccus denitrificans* ISTOD1. Bioresour Technol 242:334–343

Medhi K, Thakur IS (2018) Bioremoval of nutrients from wastewater by a denitrifier *Paracoccus denitrificans* ISTOD1. Bioresour Technol Rep 1:56–60

Nagadomi H, Takahasi T, Sasaki K, Yang HC (2000) Simultaneous removal of chemical oxygen demand and nitrate in aerobic treatment of sewage wastewater using an immobilized photosynthetic bacterium of porous ceramic plates. World J Microb Biot 16:57–62

Nancharaiah YV, Mohan SV, Lens PNL (2016) Recent advances in nutrient removal and recovery in biological and bioelectrochemical systems. Bioresour Technol 215:173–185

Nancharaiah YV, Sarvajith M (2019) Aerobic granular sludge process: a fast growing biological treatment for sustainable wastewater treatment. Curr Opin Environ Sci Health 12:57–65

Nielsen PH, McIlroy SJ, Albertsen M, Nierychlo M (2019) Re-evaluating the microbiology of the enhanced biological phosphorus removal process. Curr Opin Biotechnol 57:111–118

Park Y, Park S, Yu J, Torres CI, Rittmann BE, Lee T (2017) Complete nitrogen removal by simultaneous nitrification and denitrification in flat-panel air-cathode microbial fuel cells treating domestic wastewater. Chem Eng 316:673–679

Parsons S (ed) (2004) Advanced oxidation processes for water and wastewater treatment. IWA Publishing, London

Parsons SA, Smith JA (2008) Phosphorus removal and recovery from municipal wastewaters. Elements 4:109–112

Qi Y, Xiaoming L, Guangming Z, Shan X, Jingjin L (2003) Cultivation of aerobic granular sludge for simultaneous nitrification and denitrification in SBR system. J Environ Sci-China 24:94–98

Qiu X, Wang T, Zhong X, Du G, Chen J (2012) Screening and characterization of an aerobic nitrifying-denitrifying bacterium from activated sludge. Biotechnol Bioproces Eng 17:353–360

Rajta A, Bhatia R, Setia H, Pathania P (2019) Role of heterotrophic-aerobic denitrifying bacteria in nitrate removal from wastewater. J Appl Micro Biol 128:1261–1278

Rasoul-Amini S, Montazeri-Najafabady N, Shaker S, Safari A, Kazemi A, Mousavi P, Mobasher MA, Ghasemi Y (2014) Removal of nitrogen and phosphorus from wastewater using microalgae free cells in bath culture system. Biocatal Agric Biotechnol 3:126–131

Ren Y, Ngo HH, Guo W, Wang D, Peng L, Ni BJ, Liu Y (2020) New perspectives on microbial communities and biological nitrogen removal processes in wastewater treatment systems. Bioresour Technol 297:122491

Rout PR, Bhunia P, Dash RR (2017) Simultaneous removal of nitrogen and phosphorous from domestic wastewater using *Bacillus cereus*GS-5 strain exhibiting heterotrophic nitrification, aerobic denitrification and denitrifying phosphorous removal. Bioresour Technol 244:484–495

Rout PR, Dash RR, Bhunia P, Rao S (2018) Role of *Bacillus cereus* GS-5 strain on simultaneous nitrogen and phosphorous removal from domestic wastewater in an inventive single unit multi-layer packed bed bioreactor. Bioresour Technol 262:251–260

Rubio-Rincon FJ, Weissbrodt DG, Lopez-Vazquez CM, Welles L, Abbas B, Albertsen M, Brdjanovic D (2019) "*Candidatus Accumulibacter delftensis*": A clade IC novel polyphosphate-accumulating organism without denitrifying activity on nitrate. Water Res 161:136–151

Saha A, Bhushan S, Mukherjee P, Chanda C, Bhaumik M, Ghosh M, Sharmin J, Datta P, Banerjee S, Barat P, Thakur AR (2018) Simultaneous sequestration of nitrate and phosphate from wastewater using a tailor-made bacterial consortium in biofilm bioreactor. J Chem Technol 93:1279–1289

Salehi S, Cheng KY, Heitz A, Ginige MP (2019) Simultaneous nitrification, denitrification and phosphorus recovery (SNDPr)-An opportunity to facilitate full-scale recovery of phosphorus from municipal wastewater. J Environ Manage 238:41–48

Santos VA, Marchal LM, Tramper J, Wijffels RH (1996) Modeling and evaluation of an integrated nitrogen removal system with microorganisms co-immobilized in double-layer gel beads. Biotechnol Prog 12:240–248

Savci S (2012) An agricultural pollutant: chemical fertilizer. IJESD 3:73

Sharma S, Bhattacharya A (2017) Drinking water contamination and treatment techniques. Appl Water Sci 7:1043–167

Shen N, Zhou Y (2016) Enhanced biological phosphorus removal with different carbon sources. J Appl Microbiol 100:4735–4745

Shen Y, Gao J, Li L (2017) Municipal wastewater treatment via co-immobilized microalgal-bacterial symbiosis: microorganism growth and nutrients removal. Bioresour Technol 243:905–913

Stein LY (2011) Heterotrophic nitrification and nitrifier denitrification. In: Ward BB, Arp DJ, Koltz MG (eds) Nitrification. ASM Press, Washington, DC, pp 95–114

Stokholm-Bjerregaard M, McIlroy SJ, Nierychlo M, Karst SM, Albertsen M, Nielsen PH (2017) A critical assessment of the microorganisms proposed to be important to enhanced biological phosphorus removal in full-scale wastewater treatment systems. Front Microbiol 8:718

Su X, Xue B, Wang Y, Hashmi MZ, Lin H, Chen J, Sun F (2019) Bacterial community shifts evaluation in the sediments of Puyang River and its nitrogen removal capabilities exploration by resuscitation promoting factor. Ecotoxicol Environ Saf 179:188–197

Tang M, Jiang J, Lv Q, Yang B, Zheng M, Gao X, Yang Y (2020) Denitrification performance of *Pseudomonas fluorescens* Z03 immobilized by graphene oxide-modified polyvinyl-alcohol and sodium alginate gel beads at low temperature. R Soc Open Sci 7:191542

Taylor SM, Yiliang H, Bin Z, Huang J (2009) Heterotrophic ammonium removal characteristics of an aerobic heterotrophic nitrifying-denitrifying bacterium, *Providencia rettgeri* YL. Int J Environ Sci 21:1336–1341

Thakur IS, Medhi K (2019) Nitrification and denitrification processes for mitigation of nitrous oxide from waste water treatment plants for biovalorization: Challenges and opportunities. Bioresour Technol 282:502–513

Topare NS, Attar SJ, Manfe MM (2011) Sewage/wastewater treatment technologies: a review. Sci Revs Chem Commun 1:18–24

van Niftrik L, Jetten MS (2012) Anaerobic ammonium-oxidizing bacteria: unique microorganisms with exceptional properties. Microbiol Mol Biol Rev 76:585–596

Wan W, He D, Xue Z (2017) Removal of nitrogen and phosphorus by heterotrophic nitrification-aerobic denitrification of a denitrifying phosphorus-accumulating bacterium *Enterobacter cloacae*HW-15. Ecol Eng 99:199–208

Wang H, Song Q, Wang J, Zhang H, He Q, Zhang W, Song J, Zhou J, Li H (2018) Simultaneous nitrification, denitrification and phosphorus removal in an aerobic granular sludge sequencing batch reactor with high dissolved oxygen: effects of carbon to nitrogen ratios. Sci Total Environ 642:1145–1152

Wang J, Gong B, Huang W, Wang Y, Zhou J (2017) Bacterial community structure in simultaneous nitrification, denitrification and organic matter removal process treating saline mustard tuber wastewater as revealed by 16S rRNA sequencing. Bioresour Technol 228:31–38

Wang P, Yuan Y, Li Q, Yang J, Zheng Y, He M, Geng H, Xiong L, Liu D (2013) Isolation and immobilization of new aerobic denitrifying bacteria. Int Biodeter Biodegr 76:12–17

Wang Q, Jia W, Zhang J, Li C, Yang W (2016) Nutrients removal and nitrous oxide emission during simultaneous nitrification, denitrification, and phosphorus removal process: impact of temperature. Desalin Water Treat 57:26187–26195

Wei D, Shi L, Yan T, Zhang G, Wang Y, Du B (2014) Aerobic granules formation and simultaneous nitrogen and phosphorus removal treating high strength ammonia wastewater in sequencing batch reactor. Bioresour Technol 171:211–216

Winkler MK, Straka L (2019) New directions in biological nitrogen removal and recovery from wastewater. Curr Opin Biotechnol 57:50–55

Xia L, Li X, Fan W, Wang J (2020) Heterotrophic nitrification and aerobic denitrification by a novel *Acinetobacter* sp. ND7 isolated from municipal activated sludge. Bioresour Technol 7:122–749

Xia S, Li J, Wang R, Li J, Zhang Z (2010) Tracking composition and dynamics of nitrification and denitrification microbial community in a biofilm reactor by PCR-DGGE and combining FISH with flow cytometry. Biochem Eng J 49:370–378

Xie J, Feng N, Wang R, Guo Z, Dong H, Cui H, Liu X (2020) A reusable biosorbent using Ca-alginate immobilized *providencia vermicola* for Pd (II) recovery from acidic solution. Water Air Soil Pollut 231:1–12

Yang L, Ren YX, Zhao SQ, Liang X, Wang JP (2016) Isolation and characterization of three heterotrophic nitrifying-aerobic denitrifying bacteria from a sequencing batch reactor. Ann Microbiol 66:737–747

Yang S, Yang F, Fu Z, Wang T, Lei R (2010) Simultaneous nitrogen and phosphorus removal by a novel sequencing batch moving bed membrane bioreactor for wastewater treatment. J Hazard Mater 175:551–557

Yang Y, Lin E, Sun S, Tao X, Zhong L, Hu K (2018) Piggery wastewater treatment by *Acinetobacter sp*. TX5 immobilized with spent mushroom substrate in a fixed-bed reactor. Sci Total Environ 644:1460–1468

Yilmaz G, Lemaire R, Keller J, Yuan Z (2008) Simultaneous nitrification, denitrification, and phosphorus removal from nutrient-rich industrial wastewater using granular sludge. Biotechnol Bioeng 100:529–541

Yin J, Zhang P, Li F, Li G, Hai B (2015) Simultaneous biological nitrogen and phosphorus removal with a sequencing batch reactor–biofilm system. Int Biodeterior Biodegrad 103:221–226

Yokoyama K, Jinnai K, Sakiyama Y, Touma M (2012) Contribution of fungi to acetylene-tolerant and high ammonia availability-dependent nitrification potential in tea field soils with relatively neutral pH. Appl Soil Ecol 62:37–41

Yuan Q, Oleszkiewicz J (2010) Interaction between denitrification and phosphorus removal in a sequencing batch reactor phosphorus removal system. Water Environ Res 82:536–540

Zahn JA, Duncan C, DiSpirito AA (1994) Oxidation of hydroxylamine by cytochrome P-460 of the obligate methylotroph *Methylococcus capsulatus* Bath. J Bacteriol 176:5879–5887

Zhang DQ, Jinadasa KB, Gersberg RM, Liu Y, Tan SK, Ng WJ (2015) Application of constructed wetlands for wastewater treatment in tropical and subtropical regions (2000–2013). Int J Environ Sci 30:30–46

Zhang M, Pan L, Liu L, Su C, Dou L, Su Z, He Z (2020) Phosphorus and nitrogen removal by a novel phosphate-accumulating organism, *Arthrobacter* sp. HHEP5 capable of heterotrophic nitrification-aerobic denitrification: Safety assessment, removal characterization, mechanism exploration and wastewater treatment. Bioresour Technol 312:123633

Zhang N, Chen H, Lyu Y, Wang Y (2019) Nitrogen removal by a metal-resistant bacterium, *Pseudomonas putida* ZN1, capable of heterotrophic nitrification–aerobic denitrification. J Chem Technol Biot 94:1165–1175

Zhang QL, Liu Y, Ai GM, Miao LL, Zheng HY, Liu ZP (2012) The characteristics of a novel heterotrophic nitrification–aerobic denitrification bacterium, *Bacillus methylotrophicus* strain L7. Bioresour Technol 108:35–44

Zhang SH, Huang Y, Hua YM (2010) Denitrifying dephosphatation over nitrite: effects of nitrite concentration, organic carbon, and pH. Bioresour Technol 101:3870–3875

Zhao B, He YL, Huang J, Taylor S, Hughes J (2010) Heterotrophic nitrogen removal by *Providencia rettgeri* strain YL. J Ind Microbiol Biot 37:609–616

Zhao J, Wang X, Li X, Jia S, Wang Q, Peng Y (2019) Improvement of partial nitrification endogenous denitrification and phosphorus removal system: Balancing competition between phosphorus and glycogen accumulating organisms to enhance nitrogen removal without initiating phosphorus removal deterioration. Bioresour Technol 281:382–391

Zhou S, Borjigin S, Riya S, Terada A, Hosomi M (2014) The relationship between anammox and denitrification in the sediment of an inland river. Sci Total Environ 490:1029–1036

Zhou W, Li Y, Min M, Hu B, Zhang H, Ma X, Li L, Cheng Y, Chen P, Ruan R (2012) Growing wastewater-born microalga *Auxenochlorella protothecoides* UMN280 on concentrated municipal wastewater for simultaneous nutrient removal and energy feedstock production. Appl Energ 98:433–440