Int.J.Curr.Microbiol.App.Sci (2023) *12*(04): 37-47

International Journal of Current Microbiology and Applied Sciences
ISSN: 2319-7706 **Volume 12 Number 4 (2023)**
Journal homepage: http://www.ijcmas.com

Review Article https://doi.org/10.20546/ijcmas.2023.1204.005

Anammox Process for Wastewater Nutrient Removal: Recent Trends and Future Prospects

Khushi Gandhi[1], Molly Dua[1], Huda Afreen[2]* and Ravi Kant Singh[1]*

[1]Amity Institute of Biotechnology, Amity University Uttar Pradesh, Noida, UP-201313, India
[2]Department of Biotechnology, Dr. D. Y. Patil Biotechnology and Bioinformatics Institute, Dr. D. Y. Patil Vidyapeeth, Pune, Maharashtra, India

**Corresponding author*

Keywords

Anammox, Anamoxasomes, Nitrogen-rich wastewater, Biological Nutrient Removal

Article Info

Received:
01 March 2023
Accepted:
06 April 2023
Available Online:
10 April 2023

ABSTRACT

Anammox (an abbreviation for anaerobic ammonium oxidation) is a reaction where specialized microorganisms with anamoxasomes carry out coupled oxidation reduction process where ammonium is oxidized, and nitrite is reduced to form dinitrogen. Here, nitrite is used as the electron acceptor under anoxic conditions. Anamoxasomes (phylum Planctomycetes) are strict anaerobes hence oxygen is not required for this process for treating nitrogen-rich wastewater. The Anammox process was discovered by Mulder in 1995 to avoid the need to add additional COD (chemical oxygen demand) to the system, it functions as an effective and affordable biological nutrient removal procedure in wastewater treatment. It is mainly done to protect the quality of the water body that it is discharged into. Algal bloom which is caused by fixed nitrogen such as ammonium and nitrate is avoided. Anammox is used as a better alternative approach for the removal of nitrogen from wastewater treatment as the bacteria requires less energy, reduces CO_2 emissions, produces less excess sludge. It is also known as a low-energy consuming and ecofriendly technology. We can also observe increasing importance of anammox process. Therefore, this study reviews and discusses the current developments in anammox combined processes and its impact on wastewater treatment techniques.

Introduction

Anaerobic ammonia oxidation (anammox) is known to be one of the most ingenious discoveries fabricated for the treatment of wastewater having high ammonia nitrogen concentrations. Due to the rapid development and urbanization, nitrogen pollution has become a greater cause of concern in recent years (Wen *et al.*, 2020). The consumption of nitrogen fertilizers and discharge standards of sewage are the mainstream causes of factors affecting terrestrial and aquatic environments furtherleading to a possibility to acidification at a global scale.(Gruber and Galloway, 2008). The fundamental nitrogen removal process is the traditionally used nitrification and denitrification process. Nitrification, a two-step process, is generally carried out by aerobic, autotrophic bacteria that oxidize ammonium to nitrite ion and nitrite ion to nitrate ion with molecular oxygen as electron acceptor. It is catalysed by chemolithoautotrophic microorganisms oxidizing either ammonia or nitrite (Helder and De Vries, 1983). Nitrite and nitrate are then reduced to dinitrogen by denitrifying bacteria, which brings the complete removal of nitrate to harmless nitrogen gas as the end product. The denitrifying bacteria contributing to nitrate removal which are functioning in nitrite accumulation and or complete denitrification. The different requirements of nitrifiers and denitrifies have led to a number of reactor combinations for the removal of nitrogen from wastewater (Hu *et al.,* 2011). There is a huge risk, and these traditional methods can therefore not be used due to several issues impending large-scale application of bio-denitrification (Wang and Wang, 2013).

Moreover, there are several limitations of the traditional nitrification and denitrification process that have gradually perceived and emerged, these include, extremely high energy consumption, high operational expenses and merely any removal of ammonia nitrogen (Jetten *et al.,* 2001). Hence, the Anammox process has significant advantages for energy saving and sludge reduction, also having a significant effect on the capital costs and greenhouse gasses emissions being reduced (Blackburne *et al.,* 2008).

This study reviews the research and evolutionof anammox process, along with the microbial and technological aspects of the treatment. According to the current situation of wastewater treatment, the future development of anammox is also proposed and the potential application of anammox is prospected.

Stoichiometric Equations of Anammox Reaction

The anammox method is primarily focused on removal of ammonium from wastewater. It has two distinct steps when applied in the wastewater treatment. The first phase is ammonia oxidising bacteria partial nitrification (nitritation) converting half of the ammonium to nitrite:

$$2NH^{+}_{4} + 3O_2 \rightarrow 2NO^{-}_{2} + 4H^{+} + 2H_2O$$

The resultant ammonium and nitrite are transformed by anammox bacteria into dinitrogen gas and water through a proportionating reaction:

$$NH^{+}_{4} + NO^{-}_{2} \rightarrow N_2 + 2H_2O \text{ (8,9)}$$

Figure 1 shows the above reactions that takes place inside an anammox bacterial cell, along with the help of various enzymes.

Microbial Wastewater Treatment

Anammox microorganisms are autotrophs, anaerobes (as oxygen is not required for this metabolic process) and belong to phylum-*Planctomycetes* and order-*Planctomycetales.*
Six potential genera, namely *Candidatus brocadia, Candidatus kuenenia, Candidatus jettenia, Candidatus anammoxoglobus, Candidatus anammoximicrobium* and *Candidatus scalindua,* are included in the category of anammox bacteria (Zhang *et al.,* 2017). Table 1 includes a few examples of such researched anammox bacterial species in wastewater treatment.

These bacterias are specialized microorganisms having a membrane-bound compartment inside their cells called anammoxosome where the anammox reaction takes place (van Niftrik *et al.,* 2004). The anammox reaction proceeds with the help of enzymes in the membrane catalyzing the oxidation and reduction process in which ammonium is oxidized and nitrite is reduced to form dinitrogen. It is known that the anaerobic oxidation of ammonia proceeds via hydrazine (N2H4) and hydroxylamine, a volatile and toxic intermediate. Hydrazine is confined within anammoxosome membrane, thus avoiding the toxic effect it can cause on the anammox microorganism if it lasts for a longer period of time. Further, it is surrounded by a ladderane lipid membrane which is highly compact (5.10F: Anammox [Internet].). In primary wastewater treatment, the major forms of nitrogen present in effluent are organic nitrogen and ammonium. However, in the secondary treatment these two forms are converted to nitrate by nitrifying bacteria, such as ammonium oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB).

The anammox bacteria consists of a well-structured and systematic procedure that removes high concentrations of ammonium compounds from industrial and urban wastewater and convert them to dinitrogen (Zhang *et al.,* 2015). The process seems to be the most promising for energy-neutral or energy-generating wastewater plant treatment (WWPTs). (Gruber and Galloway, 2008; Reimann *et al.,* 2015) Microbial treatment plays an essential role in both conventional autotrophic nitrogen removal and advanced nitrogen removal approaches which are discussed further.

Technologies Involved in Nutrients Removal

Nitrogen and phosphorus are nutrients that are a natural part of the aquatic ecosystem. It supports the growth of algae and aquatic plants, which provides food and habitat for marine organisms. The removal of nitrogen and phosphorus in wastewater treatment is a huge concern and should be controlled due to the damage caused by it. It plays an important role in protecting the quality of the water body that it is discharged into. Fixed nitrogen (such as ammonium and nitrate) produces algal bloom which is also eliminated completely. Presence of untreated or partially treated effluent containing nitrogen and phosphorus often results in depletion of dissolved oxygen in water bodies (Gonzalez-Martinez *et al.,* 2018; Hasan *et al.,* 2021).

For many years, nitrogen/phosphorus removal is done by using conventional methods but they are not exactly effective as it does not help in reducing the concentration according to permissible limits set by Central Pollution Control Board of India (Delgadillo-Mirquez *et al.,* 2016). These treated effluents using conventional methods do not meet the standard unit, thus becoming a cause of pollution (Gonzalez-Martinez *et al.,* 2018; Hasan *et al.,* 2021). Wastewater treatment done by activated sludge is being widely used and largely recognized which comprises nitrification and denitrification as biogeochemical steps. Nitrification refers to the aerobic conversion process of ammonia or any reduced nitrogen compound to easily absorbable form of nitrogen such as, ammonium to nitrite (in oxic condition) whereas denitrification is the process of releasing nitrogen compound back to atmosphere using reduction, under anoxic condition (Orhon *et al.,* 2009). Both these processes require a catalyst also called nitrifiers- ammonia oxidizing bacteria (AOB), nitrite oxidizing bacteria (NOB), ammonia oxidizing archaea (AOA) (Gonzalez-Martinez *et al.,* 2015; Gonzalez-Martinez *et al.,* 2016). This has accelerated the need for nutrient removal technology, which is cost effective, eco-friendly, and sustainable. It can include biological processes, in variation or combination referred to as autotrophic nitrogen removal technology such as ANAMMOX-anaerobic ammonium oxidation, along with its combinations like DEMON- de-ammonification, CANON- completely autotrophic nitrogen removal over nitrate, ANITA Mox, PN-ANAMMOX - partial nitritation with anammox. These technologies have high potential efficiency, negligible sludge biomass production, low energy and oxygen required, and no external additional carbon is used therefore these solutions are regarded as the most important technology involved in removal of nutrients.

Nitrogen Removal Technologies

Several types of promising alternatives have recently emerged for removal of nitrogen from wastewater treatment. These technologies are based on the principle of metabolism of anammox bacteria and are incredibly useful with great advantages like low sludge generation, cost effectiveness and many more. The application of these technologies are implemented on a large scale including DEMON, CANON, and ANITA MOX systems consisting of one bioreactor. On the other hand, PN-ANAMMOX has two bioreactors used for the removal of nitrogen in wastewater treatment WWT (Rahimi *et al.,* 2020).

Partial nitritation anammox PN/A also commonly known as Partial Single reactor system for High activity Ammonium Removal Over Nitrite (pSHARON) refers to the formation of nitritefromthe ammonium present in wastewater, through oxidation. The oxidation of nitrite to nitrate must be prevented to only achieve partial nitrification. This is achieved by metabolism of autotrophic ammonium-oxidizing microorganisms (AOB)- *Nitrosomonas europaea, N. eutropha and Nitrosospira.* (Rahimi *et al.,* 2020) PN/A process is an efficient and economical method for nitrogen removal in wastewater treatment as ammonium and nitrite can be further converted to dinitrogen gas by anammox bacteria through autotrophic nitrogen removal process.

DEMON technology (the Deammonification system) aids in reducing high strength ammonia levels by utilizing granular anaerobic ammonium oxidizing bacteria biomass in a single bioreactor. It is operated by alternating cycles of aeration as well as no aeration that are controlled by pH maintaining a balance between aerobic and anaerobic conditions and biomass selection and retention causing stability. This technology uses less aeration and attains 25% of cost and energy saving in relation to conventional nitrogen removal systems, making it remarkably energy friendly (Demon Deammonification [Internet], 2023).

The CANON system that stands for Completely Autotrophic Nitrogen Removal Over Nitrite, potentially removes ammonium from wastewater in a single, oxygen-limited treatment step. Ideal environmental conditions required for the anammox reaction involving the limitation of oxygen that leads the oxidation of ammonium to nitrite, is created. However, it avoids the oxidation of nitrite to nitrate (Third *et al.,* 2001). ANITA Mox technology is a single-stage nitrogen removal process that includes the presence of carriers. This is performed in two steps; aerobic nitration (through AOBs) and anoxic ammonia oxidation performed by anammox bacteria (Christensson *et al.,* 2013).

To summarize, there are several technologies based on Anammox processes used for the removal of nitrogen from wastewater providing maximum efficiency and fulfilling the environmental and economic factors. There is a huge scope to experiment and research on such technologies.

Phosphorus Removal Technologies

The possible pathway for removal of phosphorus is usually the same as that of nitrogen. But it can also be achieved through chemical removal which involves addition of calcium, iron or aluminium salt to obtain a precipitate, advanced biological treatment that consists of uptake of phosphorus in excess of normal bacterial metabolic requirements or often a combination of both is used (Yeoman *et al.,* 1988).

Operational Studies on Anammox Processes

Research on Anammox is majorly focused on making the removal of nutrients from wastewater more efficient. Examples of such progresses include:

Controlling denitrification for achieving denitrification

Denitrifying biocommunities often comprise microorganisms with highly varied nitrate and nitrite reductase activity. Denitrifiers are classified into three types based on their capacity to decrease nitrate or nitrite - groups A, B and C (Martienssen, 1997). In general, all three categories of denitrifiers (A, B, and C) coexist in activated sludge or biofilms (Ma *et al.,* 2020).

Increasing the quantity of denitrifiers from groups A and C in the reactor might result in nitrite build up during denitrification. High pH conditions aided in reaching this aim (Qian *et al.,* 2019; Shi *et al.,* 2019; Si *et al.,* 2018). Denitrification is a self-alkalization process, therefore high pH conditions in an anoxic denitrification zone are readily maintained, which is helpful to nitrite buildup in denitrification. Until now, nitrite buildup has primarily been accomplished in a single SBR, USB, or biofilm reactor supplied with nitrate, ammonia, and organic matter (Cao *et al.*, 2016; Cui *et al.*, 2017; Du *et al.*, 2016; Ma *et al.*, 2017).

Controlling denitritation in a plug-flow wastewater treatment system, such as the commonly used anoxic/oxic (A/O) process, may be accomplished by creating a denitrifying biofilm and restricting it to the anoxic zone with the greatest pH throughout the operation (Ma *et al.*, 2020; Li *et al.*, 2019).

Nitrite accumulation can be reduced by denitrifiers using an external or endogenous organic carbon source. To control denitritation, denitrification should be finished as soon as denitratation is complete. This could be achieved via two methods:

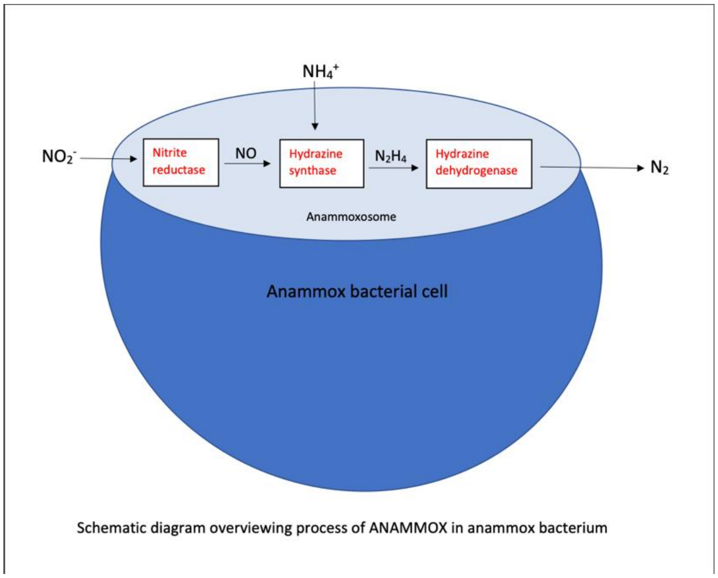
Controlling influent Carbon / Nitrogen ratio to a low level

Controlling hydraulic retention time (HRT) (Ma *et al.*, 2020)

Table.1 Examples of Anammox Bacterial Species

S. No.	Name	Remarks	Reference
1.	CandidatusBrocadiaanammoxidans	was the first organism to be identified that could oxidise ammonium in an anaerobic environment.	(12)
2.	CandidatusBrocadiafulgida	Is not only competent anammox bacterium but also its biofilm aggregates exhibit strong autoinflurescence.	(13)
3.	CandidatusKueneniastuttgartiensis	thrives not only in aerobic zones but also in summer and winter circumstances, which helps wastewater treatment by improving nitrogen removal.	(14)
4.	CandidatusAnammoximicrobiummoscowii	was able to maintain activity while surviving for a long time without nutrients. For instance, after 90 days of no substrate being fed into the laboratory flow reactor, the rate of ammonium oxidation with nitrite was recovered after two days.	(15)

Fig.1 Schematic diagram overviewing process of Anammox in Anammox Bacterium(10)



Retention of Anammox Biomass

Given that the bacterial population's growth rate is slow, maintaining anammox biomass is essential for the one-stage anammox process to operate consistently (Kartal *et al.*, 1979). Typically, the number of anammox bacteria directly affects the output of an anammox bioreactor (Strous *et al.*, 1999). According to recent research, growing granular sludge and using carrier materials to produce biofilms can be effective ways to maintain anammox biomass (Jia *et al.*, 2017; Lv *et al.*, 2016; Li *et al.*, 2018).

Anammox Biofilms

Both biofilm and granular sludge are highly aggregated. However, connected carriers are required for biofilm formation. Different carriers have been extensively researched in order to improve the wall growth characteristics of anammox bacteria (Li *et al.*, 2018). For example, zeolite particles were used as a carrier material to construct the biofilm, increasing anammox biomass enrichment and lowering biomass wash-out in the effluent to as low as 3 mgVSS/L (Fernández *et al.*, 2008). A polyethylene sponge carrier was used to remediate the leachate in the laboratory-scale anammox-SBR (Miao *et al.*, 2016) and pilot-scale IFAS (Zhang *et al.*, 2015; Zheng *et al.*, 2016). The nitrogen removal efficiency of this carrier was high, and the biofilm protection boosted the proportion of anammox genes from 1.3% to 13.3% (Li *et al.*, 2018; Miao *et al.*, 2016).

Anammox Granular Sludge

Granular sludge, which is made up of compact particles, has a faster settling velocity and better biomass retention, reducing the quantity of biomass developing in the suspension. Attaining a high nitrogen removal rate (NRR) (Fernández *et al.*, 2008) and lowering infrastructure costs are the primary benefits of forming anammox granular sludge. So far, a laboratory-scale anammox granular sludge system (Li *et al.*, 2018) has obtained the maximum NRR of 74.3 - 76.7 kgN/(m3d) (Tang *et al.*, 2011).

Combined ANAMMOX process for Nitrogen Removal

Organic nitrogen, NH 4 + -N, and a tiny quantity of NO 2 - -N and NO 3 - -N are the primary types of nitrogen in urban home sewage. However, the concentration of NO 2 - -N cannot fulfil the need of anammox. Furthermore, because AnAOB creates nitrate throughout the anabolic phase, the anammox process's potential denitrification efficiency is only 88%.

The limits of substrate varieties and the buildup of nitrate nitrogen limit the anammox process's extensive utilisation. In light of the aforementioned issues, a combination approach centred on anammox arose as the times demanded, effectively resolving these two issues (Jiaxiu *et al.,* 2022).

The common anammox combined processes include:

Partial Nitrification Anammox (PNA)

Major functional organisms of this process include: *Nitrosomonas*, *Candidatus* Brocadia, *Candidatus* Kuenenia, and *Nitrospira.* Advantages of this process include: low operating cost, stable performance and decrease NO2 emission.

However, it is not suitable for environments with low temperature. Its nitrogen removal rate lies between 46% to 95% (Chen *et al.,* 2021; Akaboci *et al.*, 2018; Lotti *et al.,* 2014; Sumino *et al.,* 2006).

Short Range Denitrification Anammox (Partial Denitrification Anammox [PDA])

The PDA process, along with the short-range denitrification process for limiting the denitrification to the stage of NO_3^- -N conversion to NO_2^- -N and combining the anammox process was proposed in 2006. This lead to high total nitrogen removal efficiency (84.8% - 97.8%), strong impact load resistance as well as cost effective (Jiaxiu *et al.,* 2022; Sumino *et al.,* 2006).

Denitrification methane oxidation – Anammox process (DAMO)

The denitrifying anaerobic methane oxidation (DAMO) process, which relies on NO 3 - -N/NO 2 - -N, can remove NO 3 - -N/NO 2 - -N and CH 4 at the same time, and the final products are just N 2 and CO 2, making it a potentially green biological denitrification method (Raghoebarsing *et al.,* 2006). This process has very high total nitrogen removal efficiency as well (90% - 99%). The poor growth rate of DAMO functional bacteria, on the other hand, is a significant limiting factor in this coupled process (Cai *et al.,* 2015).

Future Prospects

The anammox process has a great potential in nutrients removal form wastewater and can be used in full-scale Wastewater treatment plants. In fact, various such plants have already been set up and are under investigations (Muñoz-Palazon *et al.,* 2018).

However, there are certain problems in the implementation of this technology that have the scope to be improved through further research. Long start-up time of this technology, because of the high multiplication time of annamox bacteria and little yield of biomass is one such issue (Lotti *et al.,* 2014). This area hence requires further research and development of new, efficient technologies.

Further, it is essential to address some important issues so as to make Anammox systems more accessible. Application anammox techniques at lower temperatures (10°C - 18°C) as well as lower nitrogen concentrations is the next step towards this goal (Gonzalez-Martinez *et al.,* 2018; Muñoz-Palazon *et al.,* 2018).

It is also essential to understand the exact responses of anammox communities to its environment, including different organic components and pollutants (such as drugs and antibiotics), as these are compounds are known to be resistant during the biodegradation process (Gonzalez-Martinez *et al.,* 2018; Muñoz-Palazon *et al.,* 2018). Through further research and studies, the aforementioned issues can be resolved and the anammox process can be made an integrate part of wastewater treatment.

The Anammox process is an competent and cost –

effective mode of removing high concentrations of nutrients such as nitrogen and phosphorus from waste water obtained from both urban as well as industrial areas. It is a biological process which utilizes specialized microorganisms in nutrient removal. Recent studies have suggested various methods that can further aid increasing the productivity, adaptability, and feasibility of the anammox systems. These methods include controlled denitrification, anammox biomass retention and various combined processes along with the standard anammox process. However, there still remains scope of further investigations to improve the Anammox system and make it ideal in wastewater treatment plants.

Acknowledgement

We would like to acknowledge Amity Institute of Biotechnology and Amity University, Noida campus for providing us with facilities and infrastructure of working on this review.

Conflict of Interests

The authors declare no conflict of interests.

References

5.10F: Anammox [Internet]. LibreTexts Libraries. 2022 [cited 2023 Feb 17]. Available from: https://bio.libretexts.org/Bookshelves/Microbiology/Microbiology(Boundless)/05%3A_Microbial_Metabolism/5.10%3A_Chemolithotrophy/5.10F%3A_Anammox

Akaboci TRV, Gich F, Ruscalleda M, Balaguer MD, Colprim J. Assessment of operational conditions towards mainstream partial nitritation-anammox stability at moderate to low temperature: Reactor performance and bacterial community. Chemical Engineering Journal. 2018 Oct;350:192–200. http://dx.doi.org/10.1016/j.cej.2018.05.115

Blackburne R, Yuan Z, Keller J. Demonstration of nitrogen removal via nitrite in a sequencing batch reactor treating domestic wastewater. Water Res. 2008 Apr;42(8–9):2166–76. https://doi.org/10.1016/j.watres.2007.11.029

Cai C, Hu S, Guo J, Shi Y, Xie GJ, Yuan Z. Nitrate reduction by denitrifying anaerobic methane oxidizing microorganisms can reach a practically useful rate. Water Res. 2015 Dec;87:211–7. https://doi.org/10.1016/j.watres.2015.09.026

Cao S, Li B, Du R, Ren N, Peng Y. Nitrite production in a partial denitrifying upflow sludge bed (USB) reactor equipped with gas automatic circulation (GAC). Water Res. 2016; 90:309–16. https://doi.org/10.1016/j.watres.2015.12.030

Chen H, Wang H, Chen R, Chang S, Yao Y, Jiang C, *et al.*, Unveiling performance stability and its recovery mechanisms of one-stage partial nitritation-anammox process with airlift enhanced micro-granules. Bioresour Technol. 2021 Jun;330:124961. https://doi.org/10.1016/j.biortech.2021.124961

Christensson M, Ekström S, Chan AA, Le Vaillant E, Lemaire R. Experience from start-ups of the first ANITA Mox Plants. Water Science and Technology. 2013 Jun 1;67(12):2677–84. https://doi.org/10.2166/wst.2013.156

Cui B, Liu X, Yang Q, Li J, Zhou X, Peng Y. Achieving partial denitrification through control of biofilm structure during biofilm growth in denitrifying biofilter. Bioresour Technol. 2017 Aug;238:223–31. https://doi.org/10.1016/j.biortech.2017.04.034

Delgadillo-Mirquez L, Lopes F, Taidi B, Pareau D. Nitrogen and phosphate removal from wastewater with a mixed microalgae and bacteria culture. Biotechnology Reports. 2016 Sep;11:18–26. https://doi.org/10.1016/j.btre.2016.04.003

Demon Deammonification [Internet]. WaWaTech – Wastewater Technology Sp. z o.o., Sp. k. [cited 2023 Feb 17]. Available from: https://wawa-tech.com/en/technologies/demon/

Du R, Peng Y, Cao S, Li B, Wang S, Niu M.

Mechanisms and microbial structure of partial denitrification with high nitrite accumulation. ApplMicrobiolBiotechnol. 2016 Feb 3;100(4):2011–21. https://doi.org/10.1007/s00253-015-7052-9

Fernández I, Vázquez-Padín JR, Mosquera-Corral A, Campos J L, Méndez R. Biofilm and granular systems to improve Anammox biomass retention. Biochem Eng J. 2008 Dec;42(3):308–13. https://doi.org/10.1016/j.bej.2008.07.011

Gonzalez-Martinez A, Muñoz-Palazon B, Rodriguez-Sanchez A, Gonzalez-Lopez J. New concepts in anammox processes for wastewater nitrogen removal: recent advances and future prospects. FEMS Microbiol Lett. 2018 Mar 1;365(6). https://doi.org/10.1093/femsle/fny031

Gonzalez-Martinez A, Osorio F, Morillo JA, Rodriguez-Sanchez A, Gonzalez-Lopez J, Abbas BA, *et al.*, Comparison of bacterial diversity in full scale anammox bioreactors operated under different conditions. Biotechnol Prog. 2015 Nov;31(6):1464–72. https://doi.org/10.1002/btpr.2151

Gonzalez-Martinez A, Rodriguez-Sanchez A, van Loosdrecht M C M, Gonzalez-Lopez J, Vahala R. Detection of comammox bacteria in full-scale wastewater treatment bioreactors using tag-454-pyrosequencing. Environmental Science and Pollution Research. 2016 Dec 26;23(24):25501–11. : https://doi.org/10.1007/s11356-016-7914-4

Gruber N, Galloway J N. An Earth-system perspective of the global nitrogen cycle. Nature. 2008 Jan 16;451(7176):293–6. https://doi.org/10.1038/nature06592

Hasan M N, Altaf M M, Khan N A, Khan A H, Khan A A, Ahmed S, *et al.*, Recent technologies for nutrient removal and recovery from wastewaters: A review. Chemosphere. 2021 Aug;277:130328. https://doi.org/10.1016/j.chemosphere.2021.130328

Helder W, De Vries RTP. Estuarine nitrite maxima and nitrifying bacteria (Ems-Dollard estuary). Netherlands Journal of Sea Research. 1983 Oct;17(1):1–18. https://doi.org/10.1016/0077-7579(83)90002-9

Hu B lan, Shen L dong, Xu X yang, Zheng P. Anaerobic ammonium oxidation (anammox) in different natural ecosystems. Biochem Soc Trans. 2011 Dec;39(6):1811–6. https://doi.org/10.1042/BST20110711

Jetten MSM, Wagner M, Fuerst J, van Loosdrecht M, Kuenen G, Strous M. Microbiology and application of the anaerobic ammonium oxidation (‘anammox’) process. CurrOpinBiotechnol. 2001 Jun;12(3):283–8. https://doi.org/10.1016/s0958-1669(00)00211-1

Jia F, Yang Q, Liu X, Li X, Li B, Zhang L, *et al.*, Stratification of Extracellular Polymeric Substances (EPS) for Aggregated Anammox Microorganisms. Environ Sci Technol. 2017 Mar 21;51(6):3260–8. https://doi.org/10.1021/acs.est.6b05761

Jiaxiu W, Jiaqi W, Ping Z, Baolan H, Zhenhua S. Research progress of anaerobic ammonium oxidation combined nitrogen removal process. Chin J Biotechnol [Internet]. 2022 [cited 2023 Feb 16];38(4):1351–9. Available from: https://cjb-ijournals-cn.translate.goog/html/cjbcn/2022/4/gc22041351.htm?_x_tr_sl=zh-CN&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=sc https://doi.org/10.13345/j.cjb.210484

Kartal B, Kuenen J G, van Loosdrecht M C M. Sewage Treatment with Anammox. Science (1979). 2010 May 7;328(5979):702–3. https://doi.org/10.1126/science.1185941

Khramenkov S V., Kozlov MN, Kevbrina M V., Dorofeev A G, Kazakova E A, Grachev V A, *et al.*, A novel bacterium carrying out anaerobic ammonium oxidation in a reactor for biological treatment of the filtrate of wastewater fermented sludge. Microbiology (N Y). 2013 Sep 27;82(5):628–36.

Li J, Li J, Gao R, Wang M, Yang L, Wang X, *et al.*, A critical review of one-stage anammox processes for treating industrial wastewater:

Optimization strategies based on key functional microorganisms. Bioresour Technol. 2018 Oct;265:498–505. https://doi.org/10.1016/j.biortech.2018.07.013

Li J, Peng Y, Zhang L, Liu J, Wang X, Gao R, *et al.,* Quantify the contribution of anammox for enhanced nitrogen removal through metagenomic analysis and mass balance in an anoxic moving bed biofilm reactor. Water Res. 2019 Sep;160:178–87. https://doi.org/10.1016/j.watres.2019.05.070

Lotti T, Kleerebezem R, Hu Z, Kartal B, Jetten M S M, van Loosdrecht M C M. Simultaneous partial nitritation and anammox at low temperature with granular sludge. Water Res. 2014 Dec;66:111–21. https://doi.org/10.1016/j.watres.2014.07.047

Lv Y, Chen X, Wang L, Ju K, Chen X, Miao R, *et al.,* Microprofiles of activated sludge aggregates using microelectrodes in completely autotrophic nitrogen removal over nitrite (CANON) reactor. Front Environ Sci Eng. 2016 Apr 29;10(2):390–8. https://doi.org/10.1007/s11783-015-0818-6

Ma B, Qian W, Yuan C, Yuan Z, Peng Y. Achieving Mainstream Nitrogen Removal through Coupling Anammox with Denitratation. Environ Sci Technol. 2017 Aug 1;51(15):8405–13. https://doi.org/10.1021/acs.est.7b01866

Ma B, Xu X, Wei Y, Ge C, Peng Y. Recent advances in controlling denitritation for achieving denitratation/anammox in mainstream wastewater treatment plants. Bioresour Technol. 2020 Mar;299:122697. https://doi.org/10.1016/j.biortech.2019.122697

Martienssen M. Biological treatment of leachate from solid waste landfill sites—Alterations in the bacterial community during the denitrification process. Water Res. 1997 May;31(5):1164–70. https://doi.org/10.1016/S0043-1354(96)00364-8

Miao L, Wang S, Cao T, Peng Y, Zhang M, Liu Z. Advanced nitrogen removal from landfill leachate via Anammox system based on Sequencing Biofilm Batch Reactor (SBBR): Effective protection of biofilm. Bioresour Technol. 2016 Nov;220:8–16. https://doi.org/10.1016/j.biortech.2016.06.131

Muñoz-Palazon B, Rodriguez-Sanchez A, Castellano-Hinojosa A, Gonzalez-Lopez J, van Loosdrecth M C M, Vahala R, *et al.,* Quantitative and qualitative studies of microorganisms involved in full-scale autotrophic nitrogen removal performance. AIChE Journal. 2018 Feb;64(2):457–67. https://doi.org/10.1002/aic.15925

Orhon D, GermirliBabuna F, Karahan O. Industrial Wastewater Treatment by Activated Sludge. London: IWA Publishing; 2009.

Qian W, Ma B, Li X, Zhang Q, Peng Y. Long-term effect of pH on denitrification: High pH benefits achieving partial-denitrification. Bioresour Technol. 2019 Apr;278:444–9. https://doi.org/10.1016/j.biortech.2019.01.105

Raghoebarsing A A, Pol A, van de Pas-Schoonen K T, Smolders A J P, Ettwig K F, Rijpstra W I C, *et al.,* A microbial consortium couples anaerobic methane oxidation to denitrification. Nature. 2006 Apr;440(7086):918–21. https://doi.org/10.1038/nature04617

Rahimi S, Modin O, Mijakovic I. Technologies for biological removal and recovery of nitrogen from wastewater. Biotechnol Adv. 2020 Nov;43:107570. https://doi.org/10.1016/j.biotechadv.2020.107570

Reimann J, Jetten MSM, Keltjens JT. Metal Enzymes in “Impossible” Microorganisms Catalyzing the Anaerobic Oxidation of Ammonium and Methane. In 2015. p. 257–313.

Shi L, Du R, Peng Y. Achieving partial denitrification using carbon sources in domestic wastewater with waste-activated sludge as inoculum. Bioresour Technol. 2019

Jul;283:18–27. https://doi.org/10.1016/j.biortech.2019.03.063

Si Z, Peng Y, Yang A, Zhang S, Li B, Wang B, *et al.*, Rapid nitrite production *via* partial denitrification: pilot-scale operation and microbial community analysis. Environ Sci (Camb). 2018;4(1):80–6.

Strous M, Fuerst JA, Kramer EHM, Logemann S, Muyzer G, van de Pas-Schoonen KT, *et al.*, Missing lithotroph identified as new planctomycete. Nature. 1999 Jul;400(6743):446–9. https://doi.org/10.1038/22749

Sumino T, Isaka K, Ikuta H, Saiki Y, Yokota T. Nitrogen removal from wastewater using simultaneous nitrate reduction and anaerobic ammonium oxidation in single reactor. J BiosciBioeng. 2006 Oct;102(4):346–51. https://doi.org/10.1263/jbb.102.346

Tang C J, Zheng P, Wang C H, Mahmood Q, Zhang J Q, Chen X G, *et al.*, Performance of high-loaded ANAMMOX UASB reactors containing granular sludge. Water Res. 2011 Jan;45(1):135–44. https://doi.org/10.1016/j.watres.2010.08.018

Third K A, Sliekers A O, Kuenen J G, Jetten M S M. The CANON System (Completely Autotrophic Nitrogen-removal Over Nitrite) under Ammonium Limitation: Interaction and Competition between Three Groups of Bacteria. SystApplMicrobiol. 2001 Jan;24(4):588–96. https://doi.org/10.1078/0723-2020-00077

van Niftrik LA, Fuerst JA, SinningheDamsté JS, Kuenen JG, Jetten MSM, Strous M. The anammoxosome: an intracytoplasmic compartment in anammox bacteria. FEMS Microbiol Lett. 2004 Apr 1;233(1):7–13. https://doi.org/10.1016/j.femsle.2004.01.044

Wang X M, Wang J L. Nitrate removal from groundwater using solid-phase denitrification process without inoculating with external microorganisms. International Journal of Environmental Science and Technology. 2013 Sep 20;10(5):955–60. https://doi.org/10.1007/s13762-013-0236-x

Wen R, Jin Y, Zhang W. Application of the Anammox in China-A Review. Int J Environ Res Public Health. 2020 Feb 9;17(3). https://doi.org/10.3390/ijerph17031090

Yeoman S, Stephenson T, Lester JN, Perry R. The removal of phosphorus during wastewater treatment: A review. Environmental Pollution. 1988;49(3):183–233. https://doi.org/10.1016/0269-7491(88)90209-6

Zhang L, Narita Y, Gao L, Ali M, Oshiki M, Ishii S, *et al.*, Microbial competition among anammox bacteria in nitrite-limited bioreactors. Water Res. 2017 Nov;125:249–58. https://doi.org/10.1016/j.watres.2017.08.052

Zhang L, Zhang S, Peng Y, Han X, Gan Y. Nitrogen removal performance and microbial distribution in pilot- and full-scale integrated fixed-biofilm activated sludge reactors based on nitritation-anammox process. Bioresour Technol. 2015 Nov;196:448–53. https://doi.org/10.1016/j.biortech.2015.07.090

Zheng B, Zhang L, Guo J, Zhang S, Yang A, Peng Y. Suspended sludge and biofilm shaped different anammox communities in two pilot-scale one-stage anammox reactors. Bioresour Technol. 2016 Jul;211:273–9. https://doi.org/10.1016/j.biortech.2016.03.049

How to cite this article:

Khushi Gandhi, Molly Dua, Huda Afreen and Ravi Kant Singh. 2023. Anammox Process for Wastewater Nutrient Removal: Recent Trends and Future Prospects. *Int.J.Curr.Microbiol.App.Sci.* 12(04): 37-47.
doi: https://doi.org/10.20546/ijcmas.2023.1204.005