AgriCos e-Newsletter
ISSN: 2582-7049
AgriCos e-Newsletter
Open Access Multidisciplinary Monthly Online Magazine
Volume: 06 Issue: 02 February 2025 Article No: 09

From Pollution to Purity: The Role of Bacteria in Ammonia and Nitrite Removal in Wastewater

K. K.Shrivasanthan, D.Manimekalai and M. Ponmani
Department of Aquatic Environment Management, Fisheries College and Research Institute, Tamilnadu
Dr.J.Jayalalithaa Fisheries University, Thoothukudi, Tamilnadu

SUMMARY

Ammonia-degrading bacteria (ADB) are essential to the global nitrogen cycle, mitigating ammonia toxicity and promoting ecological balance. These microorganisms, including ammonia-oxidizing bacteria (AOB), nitrite-oxidizing bacteria (NOB), and anaerobic ammonium-oxidizing (anammox) bacteria, convert ammonia into less harmful compounds through nitrification and anaerobic oxidation pathways. AOB, such as Nitrosomonas and Nitrosospira, initiate the oxidation of ammonia to nitrite, while NOB, including Nitrobacter and Nitrospira, convert nitrite to nitrate. Anammox bacteria, like Candidatus Brocadia, perform direct anaerobic conversion of ammonia and nitrite to nitrogen gas. These processes are influenced by environmental factors such as temperature, pH, and oxygen availability, with optimal conditions ensuring maximum degradation efficiency. ADB are widely applied in wastewater treatment, aquaculture, and soil remediation, achieving removal efficiencies up to 98% under optimal conditions. Emerging technologies, such as membrane-aerated biofilm reactors and bioaugmentation strategies, further enhance the potential of ADB in environmental management. Continued research into their physiology and applications promises advancements in sustainable ammonia mitigation solutions.

INTRODUCTION

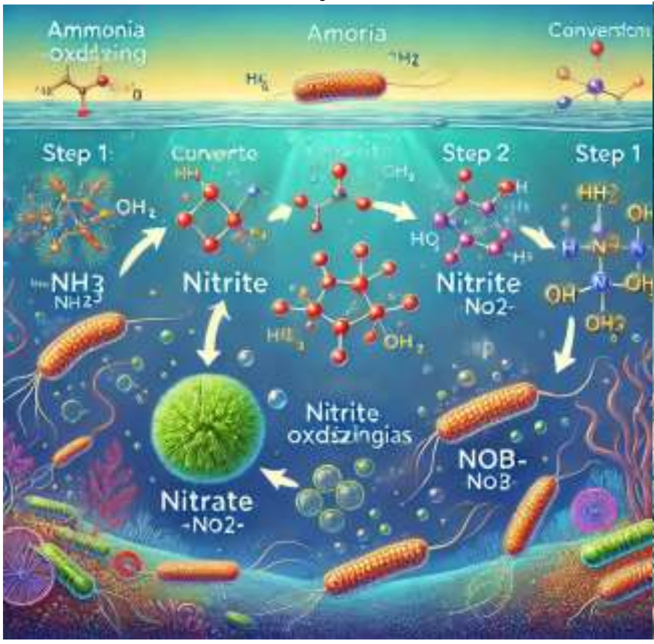
Ammonia-degrading bacteria represent a fundamental component of the global nitrogen cycle and play an indispensable role in environmental protection. These specialized microorganisms have evolved sophisticated mechanisms to convert toxic ammonia into less harmful compounds, making them essential for maintaining ecological balance and environmental health. Their applications span across various sectors, from wastewater treatment to aquaculture, where their remarkable ability to efficiently remove ammonia from diverse environments has proven invaluable in both natural ecosystems and engineered systems.

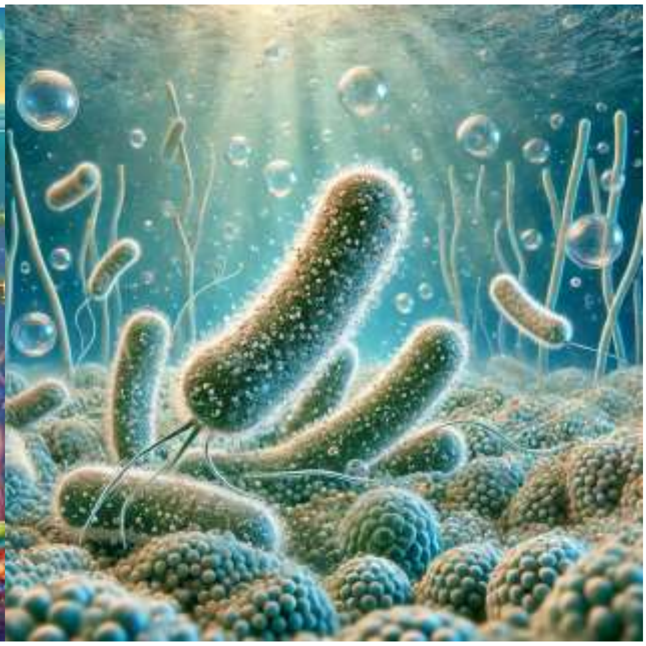
Bacterial Classification and Characteristics

Nitrifying Bacteria

The primary group of ammonia-degrading bacteria consists of nitrifying bacteria, which operate through a sophisticated two-step process. These bacteria are chemolithoautotrophs, deriving their energy from the oxidation of inorganic nitrogen compounds while using carbon dioxide as their carbon source. The process involves two distinct groups of bacteria working in tandem to complete the nitrification process. Ammonia-oxidizing bacteria (AOB) form the first group in this process. Nitrosomonas, the most extensively studied genus, demonstrates remarkable degradation efficiency ranging from 65% to 95% under optimal conditions. These bacteria possess specialized enzyme systems that enable them to initiate the ammonia oxidation process. Nitrosospira, another significant genus, exhibits particularly high efficiency in soil environments, typically achieving 50% to 80% ammonia removal. These bacteria have adapted to thrive in terrestrial ecosystems, where they play a crucial role in nitrogen cycling. In marine environments, Nitrosococcus has evolved to handle high salinity conditions, demonstrating efficiency rates of 40% to 75%. The second group, nitrite-oxidizing bacteria (NOB), completes the nitrification process. Nitrobacter, a key genus in this group, efficiently converts nitrite to nitrate with 70% to 90% efficiency. These bacteria possess specialized cytochrome systems that enable them to perform this crucial oxidation step. Nitrospira demonstrates even higher substrate affinity, achieving impressive conversion rates of 75% to 95%. This enhanced performance is attributed to their sophisticated enzyme systems and cellular adaptations. Nitrospina, specialized for marine environments, maintains efficiency rates of 60% to 85% in high-salt conditions, showcasing the diversity and adaptability of these bacterial groups.

Anammox Bacteria: The discovery of anaerobic ammonium oxidation (anammox) bacteria has revolutionized our understanding of biological nitrogen removal. These bacteria perform their unique metabolism under completely anaerobic conditions, representing a paradigm shift in nitrogen cycle biology. Candidatus Brocadia achieves remarkable ammonia removal rates of 80% to 90% in anaerobic conditions, utilizing a unique cellular compartment called the anammoxosome. Candidatus Kuenenia, another significant genus, demonstrates efficiency rates of 75% to 85% in wastewater treatment applications. The marine species Candidatus Scalindua maintains impressive efficiency rates of 70% to 80% in high-salt environments, highlighting the versatility of anammox bacteria across different ecosystems.





Degradation Mechanisms and Pathways

Aerobic Ammonia Oxidation

The aerobic degradation of ammonia follows a well-defined biochemical pathway that involves multiple enzymes and intermediate compounds. The process begins with ammonia monooxygenase (AMO), which catalyzes the oxidation of ammonia to hydroxylamine. This enzyme requires molecular oxygen as a co-substrate and represents the rate-limiting step in the process. Hydroxylamine oxidoreductase (HAO) then converts hydroxylamine to nitrite, releasing electrons that enter the electron transport chain for energy generation. The efficiency of this process is heavily influenced by environmental conditions. Optimal oxygen availability ranges from 2 to 4 mg/L, as insufficient oxygen limits the AMO activity while excessive oxygen can lead to oxidative stress. Temperature plays a crucial role, with most species showing peak performance between 25°C and 35°C. The pH range of 7.5 to 8.5 provides the ideal conditions for enzyme activity and cellular function.

Anaerobic Ammonia Oxidation

Anammox bacteria employ a unique biochemical pathway that directly combines ammonium and nitrite to produce nitrogen gas. This process occurs in the specialized anammoxosome compartment, where the reactions are carefully controlled to prevent the release of toxic intermediates. The pathway involves multiple enzyme complexes working in concert to achieve efficient nitrogen removal. The anammox process requires strict anaerobic conditions and demonstrates high temperature sensitivity, with optimal performance between 30°C and 35°C. While the start-up period for anammox systems tends to be longer due to the slow growth rate of these bacteria, once established, they can achieve remarkable efficiency levels while consuming significantly less energy compared to conventional nitrification-denitrification processes.

Environmental Factors Affecting Degradation Efficiency

Temperature Effects

Temperature significantly influences the metabolic rates and enzyme activities of ammonia-degrading bacteria. In the mesophilic range (20-35°C), these bacteria achieve their highest efficiency rates of 80-95%. This optimal temperature range supports proper protein folding, membrane fluidity, and enzyme kinetics. At lower temperatures (<20°C), efficiency drops to 40-60% due to reduced metabolic rates and enzyme activity. Conversely, temperatures above 35°C can lead to protein denaturation and membrane damage, resulting in efficiency rates of only 30-50%.

pH Influence

The pH environment plays a crucial role in determining the efficiency of ammonia degradation. The optimal pH range of 7.5-8.5 supports maximum efficiency rates of 85-95% by maintaining proper enzyme function and cellular homeostasis. Under acidic conditions (pH <6.5), efficiency drops dramatically to 20-40% due to enzyme inhibition and cellular stress. Alkaline conditions (pH >9.0) similarly reduce efficiency to 30-50% by affecting protein structure and cellular functions.

Oxygen Availability

Dissolved oxygen levels dictate the type of ammonia-degrading bacteria that can thrive in a given environment. Aerobic processes require oxygen concentrations above 2 mg/L to achieve efficiency rates of 75-95%. Under microaerobic conditions (0.5-2 mg/L), efficiency decreases to 40-60% due to limited oxygen availability for AMO activity. Anaerobic conditions support anammox bacteria, which have evolved to function efficiently without molecular oxygen.

Applications of Ammonia-Degrading Bacteria in Environmental Management

Ammonia-degrading bacteria play a crucial role in various environmental management applications, offering sustainable solutions for treating ammonia-rich environments. Their versatility and efficiency make them invaluable across multiple sectors, from wastewater treatment to ecological restoration.

In municipal wastewater treatment, these bacteria form the cornerstone of biological nitrogen removal systems. Conventional activated sludge processes utilize mixed populations of nitrifying bacteria to achieve ammonia removal efficiencies of 70-85%. Advanced treatment configurations, such as Moving Bed Biofilm Reactors (MBBR), enhance this efficiency to 80-95% by providing optimal conditions for bacterial growth on specially designed carrier materials. Membrane bioreactors represent the cutting edge of wastewater treatment, achieving remarkable ammonia removal rates of 85-98% through the combination of biological treatment and membrane filtration.

The aquaculture industry heavily relies on ammonia-degrading bacteria to maintain water quality in fish farming operations. Recirculating Aquaculture Systems (RAS) employ these bacteria in biofilters, achieving ammonia removal efficiencies of 70-90%. This application is particularly crucial as ammonia toxicity can severely impact fish health and production yields. Integrated multi-trophic aquaculture systems achieve even higher efficiency rates of 80-95% by combining different treatment approaches and bacterial populations.

Industrial wastewater treatment represents another significant application area. Food processing facilities, which often generate high-strength ammonia wastewater, utilize these bacteria to achieve treatment efficiencies of 65-85%. Chemical manufacturing plants employ specialized bacterial consortia capable of handling complex waste streams, achieving consistent ammonia removal rates of 60-80%. Agricultural runoff treatment systems, particularly those handling livestock waste, demonstrate efficiency rates of 70-90% through carefully managed bacterial populations.

Ecological restoration projects increasingly incorporate ammonia-degrading bacteria in their strategies. Constructed wetlands, designed to treat contaminated surface waters, achieve ammonia removal rates of 60-80% through the combined action of plants and bacterial communities. These systems prove particularly effective in treating agricultural runoff and maintaining water quality in sensitive ecosystems.

Landfill leachate treatment represents a challenging application where these bacteria demonstrate their versatility. Specialized treatment systems combining different bacterial groups achieve ammonia removal efficiencies of 70-85%, despite the complex nature of leachate composition. The ability of these bacteria to adapt to varying conditions makes them particularly valuable in this application.

Soil remediation projects utilize ammonia-degrading bacteria to restore contaminated land. These applications achieve efficiency rates of 50-70% in converting excess ammonia to less harmful forms, improving soil quality and supporting ecosystem recovery. The process often involves bioaugmentation with specialized bacterial strains adapted to soil conditions.

Optimization Strategies and Future Perspectives in Ammonia Degradation

Bioaugmentation represents a powerful optimization strategy that involves introducing specialized bacterial strains to existing treatment systems. This approach typically yields efficiency improvements of 10-30% by incorporating carefully selected bacteria with enhanced ammonia degradation capabilities. The success of bioaugmentation depends largely on the ability of introduced strains to establish themselves within the existing microbial community. Recent advances in strain selection and acclimation techniques have significantly improved the success rate of bioaugmentation efforts.

Process modifications have emerged as another crucial optimization avenue. Two-stage treatment systems, which separate the ammonia and nitrite oxidation phases, consistently achieve overall efficiency rates of 85-98%. This separation allows for optimal conditions to be maintained for different bacterial groups, resulting in more stable and efficient treatment processes. Hybrid systems that combine different treatment technologies have also shown promise, with efficiency rates ranging from 80-95%.

Emerging technologies are reshaping the future of ammonia degradation processes. Membrane Aerated Biofilm Reactors (MABR) represent a significant advancement, achieving remarkable efficiency rates of 90-99%. These systems utilize gas-permeable membranes to deliver oxygen directly to bacterial biofilms, optimizing oxygen transfer and reducing energy consumption. Granular sludge systems have also gained attention, demonstrating efficiency rates of 85-95% through the formation of dense, well-organized bacterial communities with superior settling properties.

CONCLUSION

Ammonia-degrading bacteria play a vital role in mitigating ammonia pollution and maintaining ecological balance. Their ability to transform ammonia into less harmful compounds makes them indispensable in wastewater treatment, aquaculture, and soil fertility management. By understanding the factors influencing their degradation efficiency and employing innovative technologies, we can harness the full potential of these microorganisms to address environmental and industrial challenges.

REFERENCES

Ali, M., Oshiki, M., Rathnayake, L., Ishii, S., Satoh, H., & Okabe, S. (2015). Rapid and successful start-up of anammox process by immobilizing the minimal quantity of biomass in PVA-SA gel beads. Water Research, 79, 147-157.

Daims, H., Lebedeva, E. V., Pjevac, P., Han, P., Herbold, C., Albertsen, M., ... & Wagner, M. (2015). Complete nitrification by Nitrospira bacteria. Nature, 528(7583), 504-509.

Gao, D., & Tao, Y. (2011). Versatility and application of anaerobic ammonium-oxidizing bacteria. Applied Microbiology and Biotechnology, 91(4), 887-894.

Jetten, M. S. M., Niftrik, L. A., Strous, M., Kartal, B., Keltjens, J. T., & Op den Camp, H. J. M. (2009). Biochemistry and molecular biology of anammox bacteria. Critical Reviews in Biochemistry and Molecular Biology, 44(2-3).

Kartal, B., Kuenen, J. G., & van Loosdrecht, M. C. M. (2010). Sewage treatment with anammox. Science, 328(5979), 702-703.

Lackner, S., Gilbert, E. M., Vlaeminck, S. E., Joss, A., Horn, H., & van Loosdrecht, M. C. M. (2014). Full-scale partial nitritation/anammox experiences – An application survey. Water Research, 55, 292-303.

Park, H., Rosenthal, A., Jezek, R., Ramalingam, K., Fillos, J., & Chandran, K. (2010). Impact of inocula and growth mode on the molecular microbial ecology of anaerobic ammonia oxidation (anammox) bioreactor communities. Water Research, 44(17), 5005-5013.

Wang, Q., Ye, L., Jiang, G., & Yuan, Z. (2014). Side-stream sludge treatment using free nitrous acid selectively eliminates nitrite oxidizing bacteria and achieves the nitrite pathway. Water Research, 55, 245-255.