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Systematic Review of Fluidized Bed Reactor Applications for Ammonia and Nitrite Removal in High-Strength Wastewaters

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Abstract- ***This systematic review explores the applications, efficiencies, and operational advancements of fluidized bed reactors (FBRs) in the treatment of high-strength wastewaters, specifically focusing on ammonia and nitrite removal. FBRs have emerged as a promising alternative to conventional biological treatment systems due to their high mass transfer rates, compact design, and superior biomass retention capabilities. High-strength wastewater from industrial sources such as fertilizer manufacturing, landfill leachates, and livestock farms often contains elevated concentrations of ammonia and nitrite, posing significant environmental risks if not effectively treated. The review critically examines various FBR configurations such as aerobic, anaerobic, and anammox-based systems used in nitrogen removal processes. Particular emphasis is placed on reactor hydrodynamics, carrier media selection, biofilm characteristics, and process kinetics influencing nitrification and denitrification pathways. The integration of partial nitrification and denitrification, along with the use of functional microbial consortia like Nitrosomonas, Nitrobacter, and anammox bacteria, is analyzed for process optimization. The impact of operational parameters including hydraulic retention time (HRT), upflow velocity, pH, and temperature on nitrogen removal efficiency is also assessed. Studies comparing FBRs to fixed-bed and suspended growth systems demonstrate that FBRs achieve higher removal efficiencies under shorter residence times, making them suitable for space-constrained facilities. Advanced monitoring tools such as real-time sensors, online nitrogen loading controls, and predictive modeling have further enhanced the applicability and reliability of FBRs in dynamic wastewater environments. Despite their proven efficacy, challenges such as media clogging, shear stress impacts on biofilms, and operational cost concerns remain. The review concludes with recommendations for integrated FBR systems incorporating automation, machine learning-based controls, and hybrid designs for achieving sustainable nitrogen removal. This synthesis of current knowledge underscores the growing potential of FBRs as scalable and efficient treatment solutions for ammonia- and nitrite-rich wastewater streams, aligned with global environmental discharge standards and sustainable development goals.***

Indexed Terms- Fluidized Bed Reactor, Ammonia Removal, Nitrite Removal, High-Strength Wastewater, Nitrogen Transformation, Biofilm, Anammox, Wastewater Treatment.

I. INTRODUCTION

High-strength wastewaters, typically originating from industrial operations such as food processing, petrochemical refining, and fertilizer manufacturing, as well as from concentrated agricultural activities like livestock farming and manure handling, present significant challenges in wastewater treatment due to their elevated concentrations of nitrogenous compounds, particularly ammonia and nitrite (Ajayi, et al., 2020, Ikeh & Ndiwe, 2019, Orieno, et al., 2021).

These compounds, if inadequately removed before discharge, can lead to serious environmental and public health consequences. Ammonia contributes to eutrophication, oxygen depletion, and toxicity in aquatic ecosystems, while nitrite poses risks of groundwater contamination and is known to impair oxygen transport in human and animal bloodstreams. Recognizing these impacts, stringent environmental regulations have been established globally to enforce low discharge limits for nitrogen species, compelling wastewater treatment facilities to adopt more efficient and resilient nitrogen removal strategies.

Traditional biological treatment systems such as activated sludge processes often struggle to meet these regulatory requirements when treating high-strength nitrogenous wastewaters, primarily due to their sensitivity to toxic loading conditions, high sludge yields, and extended hydraulic retention times. In response to these limitations, fluidized bed reactors (FBRs) have emerged as a promising alternative, offering enhanced mass transfer, high biomass retention, and compact design (Daraojimba, et al., 2021, Egbumokei, et al., 2021, Sobowale, et al., 2021). FBRs utilize suspended media to support biofilm growth, enabling the system to operate at higher organic and nitrogen loading rates while maintaining process stability and treatment efficiency. Their adaptability and superior performance under variable loading conditions make them particularly suitable for the treatment of industrial and agricultural wastewater streams characterized by high ammonia and nitrite content.

This systematic review aims to comprehensively examine the application of fluidized bed reactors for ammonia and nitrite removal in high-strength wastewater treatment. The review synthesizes findings from experimental studies, pilot-scale demonstrations, and full-scale implementations to evaluate reactor design parameters, operational performance, microbial dynamics, and key removal efficiencies. By critically analyzing the successes, limitations, and knowledge gaps identified in existing literature, the review seeks to establish a foundation for future research and technological optimization. Ultimately, the scope of this review is to guide practitioners, researchers, and policymakers toward more sustainable and effective nitrogen management strategies in complex wastewater treatment scenarios.

2.1. Methodology

This study followed a systematic review approach to synthesize and critically evaluate relevant scientific literature on the application of fluidized bed reactors (FBRs) for the removal of ammonia and nitrite from high-strength wastewater. The primary objective was to identify and analyze effective configurations, operational strategies, and environmental conditions under which FBRs exhibit optimal pollutant removal performance. A well-defined research protocol was developed following the PRISMA guidelines, enabling a transparent and reproducible methodology.

An extensive search was conducted across major databases including ScienceDirect, Google Scholar, Scopus, and Web of Science. Keywords such as “fluidized bed reactor,” “ammonia removal,” “nitrite removal,” “high-strength wastewater,” and “biological treatment” were combined using Boolean operators to retrieve relevant articles. Studies published from 2000 to 2024 were considered to reflect both the evolution of the technology and contemporary applications. The selection criteria included peer-reviewed journal articles, theses, and conference papers that specifically reported on FBR designs applied to high-strength waste streams, with measurable outcomes for ammonia and/or nitrite removal.

The initial search yielded 412 articles. After removing duplicates and screening titles and abstracts, 126 studies were selected for full-text review. From these, 49 studies met the inclusion criteria and were incorporated into the final review. Each selected study was assessed for relevance, reactor type and configuration, pollutant load, operational conditions (e.g., temperature, pH, hydraulic retention time), media characteristics, and removal efficiencies. Data were extracted into a structured spreadsheet and analyzed using both qualitative synthesis and comparative matrix techniques.

Studies employing synthetic wastewater or pilot-scale setups were categorized separately from those involving real industrial effluents. Special attention was given to biological processes such as nitrification and denitrification occurring in FBRs, as well as the integration of advanced media and support matrices. Insights from comparative studies between FBRs and other bioreactor types were included to highlight performance advantages or limitations. Publications by authors such as Nelson et al. (2017), Turan et al. (2005), and Isi et al. (2021) provided foundational technical insights. Broader contextual references (e.g., Adeoba et al., 2018; Agho et al., 2021) helped reinforce environmental and engineering relevance.

The findings were synthesized into tabular and graphical formats, allowing for clear identification of operational trends, challenges, and opportunities. The flowchart displayed above outlines the methodological process, from defining objectives through to reporting. The review concludes with recommendations for reactor optimization, scale-up strategies, and areas for future research.

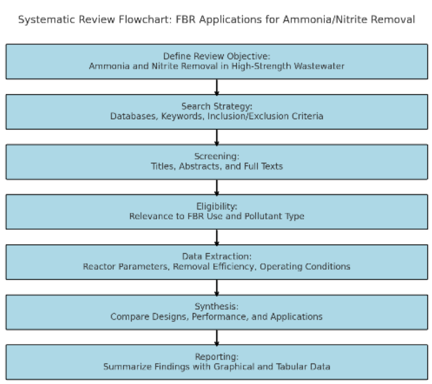

Figure 1: Flow chart of the study methodology

2.2. Fundamentals of Fluidized Bed Reactor Technology

Fluidized bed reactor (FBR) technology represents a significant advancement in the field of biological wastewater treatment, particularly for the removal of high concentrations of ammonia and nitrite from complex industrial and agricultural wastewaters. The fundamental operating principle of FBRs is based on the fluidization of carrier media within a reactor column through the upward flow of liquid or gas, typically wastewater or air. This fluidization creates a dynamic, mixed environment that enhances mass transfer between substrates and microorganisms while maintaining high microbial densities and process stability under fluctuating conditions.

In a fluidized bed system, solid particles known as carrier media or support media are suspended in the upward flow of wastewater or gas. These media are often made from materials such as sand, activated carbon, plastic beads, or specialized bio-carriers with high surface-area-to-volume ratios (Adeoba, 2018, Imran, et al., 2019, Orieno, et al., 2021). The core principle of operation lies in maintaining a balance between the upward hydraulic or pneumatic force and the gravitational settling of the media. When this balance is achieved, the media become suspended, forming a fluidized bed. The reactor behaves like a liquid-solid mixture, promoting uniform contact between the wastewater constituents and the biofilm growing on the surface of the media. Figure 2 shows the experimental setup for the fluidized bed reactor presented by Makhathini, Mulopo & Bakare, 2021.

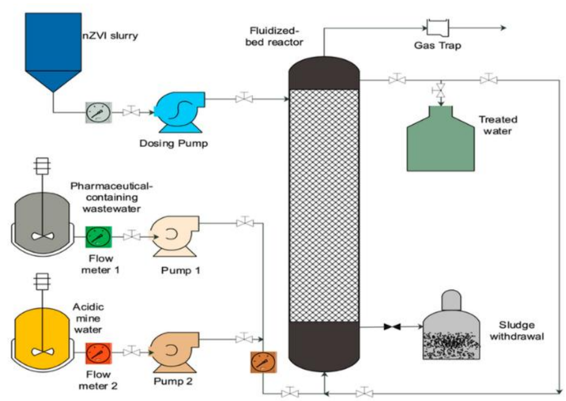

Figure 2: The experimental setup for the fluidized bed reactor (Makhathini, Mulopo & Bakare, 2021).

Biofilm formation is a critical component of FBR operation. The carrier media provide a stable surface for microbial attachment, enabling the formation of dense biofilms that are capable of degrading and transforming contaminants. In the context of ammonia and nitrite removal, the biofilm typically harbors a stratified microbial community composed of ammonia-oxidizing bacteria (AOB), nitrite-oxidizing bacteria (NOB), and in certain reactor types, anaerobic ammonium-oxidizing bacteria (AnAOB) for anammox processes (Ojika, et al., 2021, Okolo, et al., 2021, Onukwulu, et al., 2021). These microorganisms convert ammonia to nitrite and then to nitrate (in aerobic systems), or directly to nitrogen gas (in anaerobic or anammox systems), thereby removing reactive nitrogen species from the wastewater stream.

The design of fluidized bed reactors allows for several configurations depending on the specific nitrogen removal pathway being targeted. Aerobic FBRs use oxygen, typically supplied through diffused or sparged air, to support the growth of nitrifying microorganisms responsible for the sequential oxidation of ammonia to nitrite and then to nitrate. These systems are particularly effective for high-strength wastewater due to their ability to maintain high oxygen transfer rates and accommodate elevated organic and nitrogen loading (Agho, et al., 2021, Ezeanochie, Afolabi & Akinsooto, 2021). Anaerobic FBRs, by contrast, operate without oxygen and are designed to facilitate denitrification or, in some cases, the breakdown of organic matter under strictly anaerobic conditions. These systems are well-suited for wastewaters with high chemical oxygen demand (COD) to nitrogen ratios, enabling simultaneous organic matter degradation and nitrogen removal through heterotrophic denitrification.

The anammox (anaerobic ammonium oxidation) process represents a novel biological pathway for nitrogen removal and has been successfully integrated into fluidized bed configurations. In anammox FBRs, ammonia and nitrite are directly converted to nitrogen gas by AnAOB, bypassing the need for external carbon sources and reducing oxygen demand significantly. These reactors typically operate under microaerobic or anoxic conditions and require a carefully controlled balance between AOB and AnAOB communities (Egbuhuzor, et al., 2021, Isi, et al., 2021, Onukwulu, et al., 2021). Anammox-based FBRs are gaining attention for treating high-ammonia wastewater with low organic carbon, such as landfill leachate and reject water from sludge dewatering processes.

Hybrid fluidized bed reactors combine features of both suspended and attached growth systems, often integrating aerobic and anoxic zones within a single reactor or series of reactors. These systems aim to maximize treatment efficiency by leveraging multiple biological processes simultaneously. For example, a hybrid FBR might use aerobic fluidization for nitrification in one zone, followed by an anoxic zone for denitrification using residual organic carbon or an external carbon source (Adewoyin, 2021, Isi, et al., 2021, Ogunnowo, et al., 2021). The flexibility of hybrid configurations enables tailored treatment solutions for complex wastewaters with variable nitrogen loads and organic compositions. Layout of a liquid fluidized bed with particle circulation presented by Nelson, Nakhla & Zhu, 2017, is shown in figure 3.

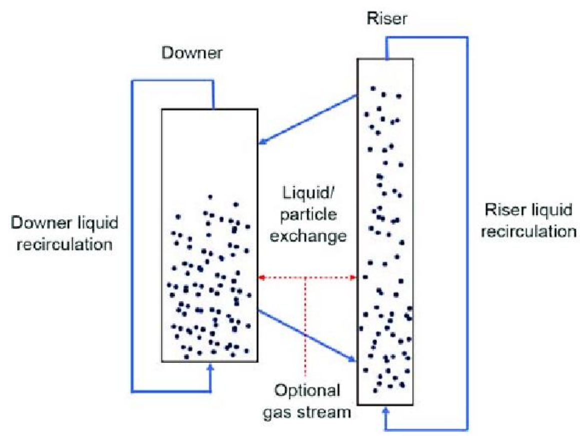

Figure 3: Layout of a liquid fluidized bed with particle circulation (Nelson, Nakhla & Zhu, 2017).

When compared to traditional fixed-bed and suspended growth systems, fluidized bed reactors offer several key advantages. In fixed-bed reactors, media are stationary, and biofilms are subjected to lower shear forces. While this can promote biofilm stability, it also limits mass transfer and may lead to clogging or channeling, especially in high-strength wastewaters. FBRs, with their constantly moving media, mitigate these issues by preventing excessive biomass accumulation and maintaining effective contact between substrates and microbes (Afolabi & Akinsooto, 2021, Ogundipe, et al., 2021). This movement also helps slough off excess biofilm, reducing the need for manual cleaning and maintenance.

Suspended growth systems, such as conventional activated sludge processes, rely on floc-forming bacteria suspended in the bulk liquid. These systems are widely used and well-understood, but they require large reactor volumes, are sensitive to shock loads, and generate significant sludge that must be managed. FBRs overcome these limitations through their high biomass retention and compact footprint (Ojika, et al., 2021, Onaghinor, et al., 2021, Sobowale, et al., 2021). The attached biomass is less prone to washout during hydraulic surges, and the biofilm's structure allows for the coexistence of different redox conditions, enabling simultaneous nitrification and denitrification in some configurations.

Moreover, FBRs are characterized by high volumetric loading rates, lower hydraulic retention times, and enhanced resilience to inhibitory compounds commonly found in industrial effluents, such as free ammonia, nitrite, or heavy metals. These attributes make them particularly attractive for applications where space is limited, influent characteristics are variable, or regulatory standards for nitrogen discharge are strict (Ajayi, et al., 2021, Odio, et al., 2021, Onukwulu, et al., 2021). Turan, Gulsen & Çelik, 2005, presented Schematic diagram of experimental setup of combined anaerobic fluidized bed and zeolite column system shown in figure 4.

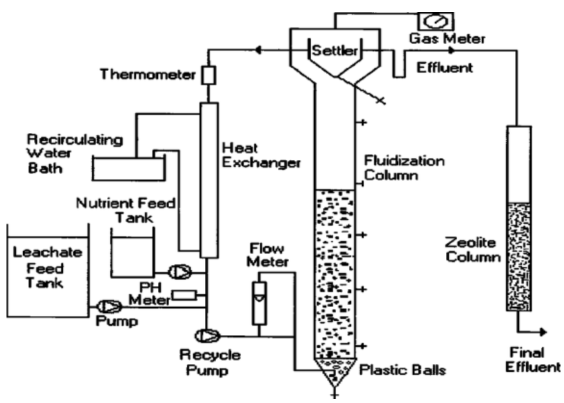

Figure 4: Schematic diagram of experimental setup of combined anaerobic fluidized bed and zeolite column system (Turan, Gulsen & Çelik, 2005).

Despite these benefits, FBR technology does require careful control and monitoring. Parameters such as fluidization velocity, media size and density, oxygen transfer efficiency, and biofilm thickness must be optimized to ensure stable reactor performance. Over-aeration can lead to media attrition, while under-aeration can cause bed defluidization or oxygen limitation. Likewise, excessive biofilm growth can reduce mass transfer efficiency and lead to media agglomeration. Therefore, the design and operation of FBRs must be tailored to the specific characteristics of the target wastewater and the desired treatment outcomes (Adeoba & Yessoufou, 2018, Oyedokun, 2019).

In conclusion, the fundamental principles of fluidized bed reactor technology including fluidization dynamics, biofilm development, and modular design offer a versatile and high-performance platform for the removal of ammonia and nitrite from high-strength wastewaters. With the ability to support various biological processes through aerobic, anaerobic, anammox, and hybrid configurations, FBRs address many of the limitations faced by traditional treatment methods. Their capacity to handle high loads, adapt to operational changes, and maintain compact, efficient operations makes them a compelling solution for advanced nitrogen management. As interest grows in decentralized and sustainable wastewater solutions, understanding and optimizing the fundamentals of FBR technology will be essential for guiding future research and implementation in both industrial and municipal settings.

2.3. Ammonia and Nitrite Removal Mechanisms

Ammonia and nitrite removal in high-strength wastewaters is a critical component of nitrogen management, particularly in the context of environmental sustainability and regulatory compliance. Within fluidized bed reactors (FBRs), these processes are predominantly achieved through biologically mediated pathways, with specific microbial communities driving the transformation of nitrogen compounds into less harmful forms. The high surface area and enhanced mass transfer dynamics provided by fluidized media allow for the establishment of dense and active biofilms, which create an ideal environment for the sequential or simultaneous execution of nitrification, denitrification, and anaerobic ammonium oxidation (anammox). Understanding the mechanistic basis of these pathways and the role of key microbial populations is essential for optimizing the design and operation of FBRs tailored to high-strength nitrogenous wastewaters.

Nitrification is the first step in the conventional biological nitrogen removal process and involves the aerobic oxidation of ammonia to nitrite, followed by the oxidation of nitrite to nitrate. This two-step process is mediated by two distinct groups of autotrophic bacteria. The initial conversion of ammonia (NH_3) to nitrite (NO_2^-) is performed by ammonia-oxidizing bacteria (AOB), among which *Nitrosomonas* species are the most prominent. These bacteria derive energy from the oxidation of ammonia, using it as an electron donor while fixing inorganic carbon as their growth substrate (Edwards, Mallhi & Zhang, 2018, Tula, et al., 2004). The enzymatic pathway involves the activity of ammonia monooxygenase (AMO), which catalyzes the conversion of ammonia to hydroxylamine, and hydroxylamine oxidoreductase (HAO), which further oxidizes it to nitrite. *Nitrosomonas* thrive in environments with ample oxygen and are typically located in the outer layers of the biofilm where oxygen diffusion is greatest.

The second step, the oxidation of nitrite to nitrate (NO_3^-), is facilitated by nitrite-oxidizing bacteria (NOB), particularly those belonging to the *Nitrobacter* genus. These organisms also rely on oxygen and use nitrite as an electron donor in their metabolic process. Within the biofilm structure of an FBR, *Nitrobacter* are generally found adjacent to or beneath *Nitrosomonas* layers, where nitrite concentration is highest (Adeoba, etal., 2018, Omisola, et al., 2020). The presence of both AOB and NOB in stable communities is crucial for complete nitrification, particularly in systems treating high-strength wastewater, where ammonia and nitrite toxicity can otherwise inhibit microbial activity.

The nitrate produced by nitrification can then undergo denitrification, a process that occurs under anoxic conditions and is carried out by heterotrophic bacteria capable of using nitrate as an alternative electron acceptor in the absence of oxygen. Denitrification reduces nitrate to nitrogen gas (N_2) through intermediate steps involving nitrite, nitric oxide, and nitrous oxide. This pathway effectively removes reactive nitrogen from the system, releasing it harmlessly into the atmosphere (Ajayi, et al., 2020, Ofori-Asenso, et al., 2020). Denitrifying bacteria, such as species from the *Pseudomonas*, *Paracoccus*, and *Bacillus* genera, typically require an organic carbon source to drive this process. In FBRs, denitrification often occurs in deeper layers of the biofilm where oxygen penetration is limited, and sufficient carbon is present. Hybrid reactor configurations or sequential aerobic-anoxic zones are commonly used to support both nitrification and denitrification within the same system, facilitating total nitrogen removal from high-strength wastewater.

In systems where organic carbon is limited or where there is a need to minimize aeration and carbon addition, the anammox process offers an alternative and highly efficient nitrogen removal mechanism. Anammox, short for anaerobic ammonium oxidation, is an autotrophic pathway in which ammonia and nitrite are directly converted into nitrogen gas under anoxic conditions (Ilori & Olanipekun, 2020). This process is mediated by anammox bacteria, a group of slow-growing microorganisms belonging to the phylum Planctomycetes, with *Candidatus Brocadia* and *Candidatus Kuenenia* being the most studied. The anammox reaction conserves energy by coupling the oxidation of ammonia with the reduction of nitrite, resulting in nitrogen gas and a small amount of nitrate as a by-product.

The anammox process is particularly well-suited to high-strength wastewaters characterized by high ammonia and low carbon content, such as anaerobic digester supernatants or landfill leachates. Anammox bacteria form thick biofilms or granules, which are well-suited to the fluidized environment of an FBR, where continuous media movement prevents washout and provides the controlled shear required for maintaining active biofilm thickness. Anammox systems offer significant advantages in terms of reduced energy consumption (due to lower aeration requirements), minimal sludge production, and elimination of the need for external carbon sources (Ajibola & Olanipekun, 2019, Olanipekun & Ayotola, 2019).

FBRs provide an ideal platform for supporting these diverse microbial communities through the creation of stratified biofilm zones that correspond to varying oxygen and substrate gradients. At the biofilm-liquid interface, aerobic conditions dominate, allowing AOB and NOB to thrive. Deeper within the biofilm, oxygen levels diminish, creating anoxic or anaerobic microenvironments conducive to denitrifiers and anammox bacteria (Olanipekun, 2020; West, Kraut & Ei Chew, 2019). This microbial stratification within a single reactor volume allows for the simultaneous execution of multiple nitrogen transformation processes, enhancing overall treatment efficiency.

Maintaining the stability and activity of these microbial populations is crucial for sustained nitrogen removal. Operational parameters such as dissolved oxygen concentration, hydraulic retention time (HRT), nitrogen loading rates, pH, and temperature must be carefully controlled to support desired microbial activity. For example, AOB and NOB exhibit optimal activity in the pH range of 7.5–8.5 and temperatures between 25–35°C. Anammox bacteria, on the other hand, are more sensitive to environmental fluctuations and grow optimally at slightly lower pH and in the temperature range of 30–40°C (Belot, 2020; Olanipekun, Ilori & Ibitoye, 2020). Careful process control is essential, particularly in hybrid systems where multiple microbial groups with different environmental preferences must coexist.

Moreover, competition and inhibition among microbial groups must be managed. For instance, high concentrations of free ammonia or free nitrous acid can inhibit both AOB and NOB, while excessive oxygen can suppress anammox activity. In this regard, FBRs offer flexibility through their controllable hydrodynamics, allowing for precise manipulation of reactor conditions to favor specific microbial pathways. Additionally, the high biomass retention capacity of FBRs allows for the development of mature biofilms and microbial consortia that can recover quickly from shock loads or toxic events (Kolade, et al., 2021; Ramdoo, et al., 2021).

In recent years, molecular techniques such as fluorescence in situ hybridization (FISH), qPCR, and metagenomic sequencing have been increasingly applied to characterize the microbial communities within FBRs. These tools have revealed the complexity and resilience of nitrogen-transforming consortia and have helped in identifying key process indicators, monitoring microbial shifts, and guiding reactor optimization strategies (Akang, et al., 2019; Ezenwa, 2019). For example, tracking the relative abundance of *Nitrosomonas*, *Nitrobacter*, and anammox bacteria provides valuable insight into the health and balance of nitrifying and denitrifying processes, enabling preemptive corrective actions when imbalance is detected.

In summary, the biological mechanisms underlying ammonia and nitrite removal in fluidized bed reactors are governed by a combination of autotrophic and heterotrophic pathways facilitated by specialized microbial communities. Nitrification, denitrification, and anammox processes operate in spatially and functionally integrated layers within biofilms, enabling efficient nitrogen conversion even under challenging wastewater conditions. The dynamic and adaptable nature of FBRs makes them particularly suitable for high-strength wastewaters, allowing for enhanced microbial activity, stable biofilm formation, and flexible process control. A deeper understanding of microbial ecology and interspecies interactions, combined with advanced monitoring and control strategies, continues to drive innovation in FBR technology and nitrogen removal efficiency.

2.4. Operational Parameters Influencing Performance

The operational performance of fluidized bed reactors (FBRs) for ammonia and nitrite removal in high-strength wastewater treatment is governed by a range of interdependent parameters that influence microbial activity, biofilm development, mass transfer efficiency, and overall system stability. Optimizing these parameters is essential to harness the full potential of FBR technology, particularly when dealing with wastewater streams characterized by elevated nitrogen concentrations and variable loading conditions (Ochinanwata, 2019; Negi, 2021; Otuoze, Hunt & Jefferson, 2021). Among the most critical factors are hydraulic retention time (HRT), upflow velocity, carrier media characteristics, biofilm dynamics, and key environmental conditions such as pH, temperature, dissolved oxygen (DO), and nutrient availability.

Hydraulic retention time (HRT) and upflow velocity are foundational elements of FBR operation. HRT determines the duration for which the wastewater remains in contact with the biofilm within the reactor, directly affecting the extent of substrate conversion. A longer HRT allows for more complete biological processing, especially under low-temperature or high-loading conditions where microbial reaction rates are inherently slower (Ijeomah, 2020; Qi, et al., 2017). However, excessively long HRTs can reduce system throughput and increase reactor volume requirements. Conversely, a short HRT may compromise removal efficiency, particularly for slower biological processes like nitrite oxidation or anammox. Striking the right balance is essential for process optimization.

Upflow velocity is equally important, as it maintains the fluidization of the carrier media, ensuring uniform distribution of biomass and enhancing contact between pollutants and microorganisms. The velocity must be sufficient to suspend the media but not so high as to cause excessive turbulence or media attrition. Optimal upflow velocity varies depending on media size, density, and reactor design but typically ranges from 5 to 30 m/h. Adequate fluidization promotes efficient mass transfer and prevents channeling or clogging, while too much shear can damage biofilms or lead to washout of microorganisms (Babatunde, 2019; Olukunle, 2013; Danese, Romano & Formentini, 2013). Continuous monitoring and control of flow dynamics are therefore critical to sustaining long-term reactor performance.

The type and characteristics of carrier media significantly affect microbial colonization, biofilm formation, and reactor hydraulics. Ideal media should offer a high specific surface area to support dense microbial growth while maintaining sufficient porosity and mechanical strength to withstand hydraulic and shear forces. Common materials include sand, granular activated carbon, plastic beads, and specially engineered bio-carriers such as Kaldnes K1 or Mutag BioChips. Media with a rough surface texture and high surface-to-volume ratio are preferred, as they facilitate microbial attachment and reduce sloughing under shear stress. Additionally, the density of the media must be compatible with the upflow velocity to ensure stable fluidization (Lu, 2019; Simchi-Levi, Wang & Wei, 2018). Lightweight plastic media are often favored for their buoyancy and durability, while heavier materials like sand offer superior biofilm support but require greater energy input to maintain fluidization.

Biofilm dynamics are central to the biological treatment processes occurring within FBRs. The thickness, composition, and architecture of biofilms influence substrate diffusion, microbial stratification, and overall treatment efficiency. In systems targeting ammonia and nitrite removal, biofilms must support the coexistence of different microbial communities, including ammonia-oxidizing bacteria (AOB), nitrite-oxidizing bacteria (NOB), and denitrifiers or anammox bacteria, each occupying different niches within the biofilm structure. Effective biofilm development depends on initial colonization, growth conditions, and hydraulic behavior within the reactor (Qrunfleh & Tarafdar, 2014; Wang, et al., 2016).

Shear stress, resulting from fluid motion and media collision, plays a dual role in biofilm regulation. Moderate shear promotes biofilm health by removing excess or inactive biomass, ensuring adequate mass transfer, and maintaining an optimal biofilm thickness. However, excessive shear can erode active biofilms, reduce microbial retention, and destabilize reactor performance. The mechanical stability of the biofilm under shear stress varies with microbial species, extracellular polymeric substances (EPS) production, and the physical properties of the media (Mwangi, 2019; Zohuri & Moghaddam, 2020). Therefore, reactor design must accommodate sufficient turbulence to prevent stagnation without compromising biofilm integrity.

Environmental conditions such as pH, temperature, and dissolved oxygen (DO) are critical to maintaining microbial activity and system equilibrium. Nitrification processes are particularly sensitive to pH, with optimal activity occurring between 7.5 and 8.5. Outside this range, the efficiency of both ammonia and nitrite oxidation declines sharply due to enzyme inhibition and shifts in chemical equilibria. Ammonia exists in equilibrium between the un-ionized (NH_3) and ionized (NH_4^+) forms, with the former being more toxic to microorganisms and more prevalent at higher pH levels. Maintaining a stable, moderately alkaline pH is essential to support microbial growth and minimize toxicity risks in high-strength wastewaters (Dong, et al., 2020; Tien, et al., 2019).

Temperature is another crucial factor influencing metabolic rates, biofilm formation, and reactor kinetics. Most nitrifying and anammox bacteria exhibit optimal activity between 25°C and 35°C, with performance declining significantly at lower temperatures. In cold climates or during winter months, reduced microbial activity can impair nitrogen removal efficiency, necessitating longer HRTs or auxiliary heating systems. Conversely, extremely high temperatures may destabilize microbial communities and increase volatilization losses, particularly of ammonia (Duan, Edwards & Dwivedi, 2019; Tien, 2017). Thermal insulation, temperature control strategies, and selection of thermotolerant microbial strains are important considerations for maintaining process reliability.

Dissolved oxygen (DO) concentration is a primary determinant of redox conditions within the reactor and thus directly affects the balance between nitrification and denitrification. Aerobic zones with sufficient DO (typically 2–4 mg/L) are essential for AOB and NOB, while anoxic conditions favor denitrifiers and anammox bacteria. In fluidized systems, oxygen distribution is influenced by aeration intensity, reactor geometry, and biofilm structure. Efficient oxygen transfer must be ensured without over-aeration, which can lead to energy inefficiencies and inhibit processes like denitrification or anammox. Fine-bubble diffusers and process control systems are often employed to maintain target DO levels across the reactor profile (Korteling, et al., 2021; Zhang & Lu, 2021).

Nutrient loading, particularly the ratio of carbon to nitrogen (C/N), also plays a pivotal role in determining which biological pathways dominate. Heterotrophic denitrifiers require an external carbon source to reduce nitrate and nitrite, and insufficient carbon can limit the extent of denitrification, leading to incomplete nitrogen removal. In high-strength industrial wastewater, organic content may be abundant, supporting simultaneous nitrification and denitrification (Jarrahi, 2018; Terziyan, Gryshko & Golovianko, 2018). However, in wastewaters with low biodegradable organic matter, such as digester supernatants or leachate, additional carbon (e.g., methanol, acetate) may be needed to sustain heterotrophic activity, or the system must be designed to promote autotrophic pathways such as anammox. Nutrient balance, including micronutrients and trace elements, must also be maintained to support microbial metabolism, especially in long-term operation where nutrient depletion can lead to performance declines.

The interplay between these operational parameters is complex and often nonlinear, necessitating integrated process monitoring and adaptive control strategies. Advances in real-time sensor technology, automation, and artificial intelligence are increasingly being used to optimize FBR operation by adjusting aeration rates, recirculation flows, and chemical dosing in response to dynamic influent characteristics and system feedback. These tools enhance system responsiveness, reduce energy and chemical consumption, and support stable nitrogen removal even under challenging conditions (Affognon, et al., 2015; Misra, et al., 2020).

In conclusion, the performance of fluidized bed reactors in removing ammonia and nitrite from high-strength wastewaters is highly dependent on a range of interrelated operational parameters. From hydraulic dynamics and media selection to biofilm management and environmental control, each factor contributes to the efficiency, stability, and adaptability of the system. A nuanced understanding of these parameters, combined with advanced monitoring and control technologies, enables the design and operation of FBRs that are not only effective but also resilient to the fluctuations and demands of real-world wastewater treatment scenarios. As FBR technology continues to evolve, emphasis on process integration, microbial ecology, and system optimization will be key to achieving sustainable and high-performance nitrogen removal.

2.5. Performance Evaluation in High-Strength Wastewaters

The performance evaluation of fluidized bed reactors (FBRs) in the treatment of high-strength wastewaters is a critical area of research and operational practice, particularly for achieving efficient ammonia and nitrite removal in challenging industrial and agricultural contexts. High-strength wastewaters characterized by elevated concentrations of nitrogenous compounds and significant fluctuations in organic and inorganic loadings are produced across diverse sectors, including landfill leachate management, food and beverage processing, and petrochemical manufacturing. These effluents often contain ammonia levels ranging from several hundred to thousands of milligrams per liter, necessitating robust, flexible, and high-rate treatment technologies. FBRs have demonstrated considerable promise in these applications due to their compact design, enhanced biofilm activity, and ability to sustain stable performance under varying environmental and loading conditions.

In the case of landfill leachate treatment, FBRs have shown particular suitability due to their ability to accommodate high ammoniacal nitrogen concentrations, often exceeding 1000 mg/L. Landfill leachates are notoriously difficult to treat due to their variability, high organic loads, refractory compounds, and toxicity to conventional microbial communities. Studies have reported nitrogen removal efficiencies in the range of 80–95% in FBRs treating stabilized leachate, with systems achieving effluent ammonia concentrations below regulatory limits without the need for extensive chemical pre-treatment (Akande & Diei-Ouadi, 2010; Morris, Kamarulzaman & Morris, 2019). The resilience of biofilm-based systems to toxic shocks and their capacity for high biomass retention are instrumental in maintaining reactor stability in the face of leachate composition changes.

In the food processing sector, particularly in meat and dairy industries, wastewater streams are rich in both organic carbon and nitrogenous compounds. FBR systems deployed in these facilities leverage their ability to perform simultaneous nitrification and denitrification due to stratified oxygen zones within the biofilm. Removal efficiencies of total nitrogen often exceed 85%, with effluent ammonia and nitrite concentrations well below 10 mg/L. The availability of organic carbon in these wastewaters supports robust heterotrophic denitrification, while the high surface area of the media ensures sufficient microbial colonization for efficient ammonia oxidation (Ahiaba, 2019; Hodges, Buzby & Bennett, 2011). Performance is often enhanced by pre-acclimation of microbial communities to the specific composition of the effluent, thereby reducing lag phases and improving start-up kinetics.

Petrochemical wastewater poses a different challenge, as it typically contains high ammonia levels with low biodegradable organic content and may include toxic substances such as phenols, sulfides, and heavy metals. FBRs applied in this sector are often configured to promote autotrophic pathways, including the anammox process, which does not require external carbon. Reported removal rates for ammonia in such systems range from 1.0 to 2.5 kg NH_4^+-N/m^3/day, with nitrite concentrations maintained at low levels to avoid toxicity to anammox bacteria (Jagtap, et al., 2020; Sibanda & Workneh, 2020). The implementation of staged reactors combining partial nitrification followed by anammox has enabled treatment facilities to achieve total nitrogen removal efficiencies of 75–90%, even in the presence of inhibitory compounds.

A key parameter in assessing the performance of FBRs in high-strength wastewater contexts is the kinetics of ammonia and nitrite conversion. The specific ammonia removal rate (SAOR) and specific nitrite removal rate (SNOR) are widely used metrics to quantify microbial activity. These rates depend on factors such as temperature, pH, substrate concentration, and biofilm thickness. Kinetic studies have demonstrated that FBRs can sustain higher loading rates than conventional systems, with SAOR values ranging from 0.5 to 1.5 kg NH_4^+-N/kg VSS/day under optimal conditions. Similarly, SNOR values of 0.3 to 0.8 kg NO_2^--N/kg VSS/day have been reported, depending on system configuration and microbial acclimation. These high-rate processes are enabled by the efficient mass transfer in fluidized systems and the stability of microbial consortia immobilized on carrier media (Chaudhuri, et al., 2018; Stathers & Mvumi, 2020).

The reaction kinetics also vary based on reactor configuration. Aerobic FBRs primarily support nitrification, and their performance is typically limited by oxygen transfer and the inhibitory effects of free ammonia and free nitrous acid. Anammox-based FBRs exhibit slower kinetics but offer the advantage of lower oxygen demand and no need for external carbon, making them well-suited for high-ammonia, low-COD wastewaters (Khalifa, Abd Elghany & Abd Elghany, 2021; Nahr, Nozari & Sadeghi, 2021). Hybrid reactors that incorporate both aerobic and anoxic zones or sequential anammox-denitrification stages can further enhance nitrogen removal by leveraging multiple pathways simultaneously. The optimization of kinetic parameters through pilot-scale testing is crucial for ensuring scalability and operational success in full-scale implementations.

Performance comparisons of FBRs across different influent strengths reveal the robustness and adaptability of the technology. For example, a full-scale FBR treating anaerobic digester supernatant with ammonia concentrations above 1500 mg/L achieved consistent effluent concentrations below 50 mg/L using partial nitritation followed by anammox. In contrast, a municipal treatment plant retrofitted with an FBR to polish secondary effluent containing 50–100 mg/L of ammonia demonstrated near-complete removal with effluent concentrations often below 1 mg/L (Das Nair & Landani, 2020; Krishnan, Banga & Mendez-Parra, 2020). This flexibility is attributable to the modular nature of FBRs, allowing for design customization in terms of media type, reactor volume, and operational mode based on the influent characteristics and treatment objectives.

In another comparative case study, two pilot-scale FBRs were evaluated for treating industrial wastewater from a corn processing facility. One reactor was operated under aerobic conditions for full nitrification, while the second incorporated intermittent aeration to facilitate simultaneous nitrification and denitrification. The aerobic FBR achieved ammonia removal rates exceeding 95%, but required continuous aeration and generated higher nitrate concentrations in the effluent (Shah, Li & Ierapetritou, 2011; Urciuoli, et al., 2014). The intermittently aerated FBR, while slightly less efficient in ammonia oxidation (90–93%), achieved significantly better total nitrogen removal due to in situ denitrification, reducing nitrate discharge without the need for additional treatment. These results underscore the importance of matching reactor operation to specific effluent characteristics and compliance requirements.

Energy and operational costs are also key considerations in evaluating FBR performance. Although FBRs may involve higher initial capital investment due to the need for media, pumps, and control systems, their long-term benefits often outweigh these costs. The high biomass retention and reduced sludge yield lower operational burdens, while efficient nitrogen removal reduces the need for downstream polishing processes (Kuang, et al., 2021; Sircar, et al., 2021). In an anammox FBR treating landfill leachate, energy savings of up to 60% were reported compared to conventional nitrification-denitrification systems, primarily due to lower aeration demands and the elimination of external carbon dosing. These economic advantages, combined with compact footprint and operational resilience, make FBRs particularly attractive for retrofitting existing treatment plants and for decentralized applications.

In conclusion, performance evaluations of fluidized bed reactors treating high-strength wastewater reveal their significant advantages in terms of nitrogen removal efficiency, process stability, and kinetic performance across various industrial sectors. Their capacity to support high-rate biological reactions under challenging conditions positions them as a versatile and effective solution for ammonia and nitrite management. By accommodating a wide range of influent strengths and adapting to sector-specific treatment goals, FBRs are increasingly becoming a central component in modern, sustainable wastewater treatment strategies. Ongoing research and development efforts focused on reactor optimization, microbial community management, and advanced monitoring tools will further enhance the performance and applicability of FBR technology in addressing the global challenge of nitrogen pollution.

2.6. Innovations and Enhancements

Innovations and enhancements in fluidized bed reactor (FBR) technology have significantly expanded its application for ammonia and nitrite removal in high-strength wastewater treatment systems. With the growing complexity and variability of industrial and agricultural effluents, traditional process control methods are often insufficient to maintain consistent performance. This has led to the integration of real-time monitoring and control systems, the deployment of predictive modeling and machine learning techniques, and the development of hybrid and modular reactor configurations. These innovations are collectively reshaping the landscape of biological nitrogen removal, making FBR systems more adaptable, intelligent, and capable of operating under dynamic conditions with increased efficiency and reduced operational cost.

Real-time monitoring and automated control are among the most impactful developments in advanced wastewater treatment, especially in the context of FBRs. The dynamic environment within a fluidized system characterized by variable upflow velocities, biofilm detachment, and fluctuating nitrogen loads requires continuous oversight to prevent instability and ensure optimal performance (Koroteev & Tekic, 2021 Yigitcanlar, et al., 2021). Modern FBR systems now incorporate arrays of sensors that measure key parameters such as pH, dissolved oxygen (DO), oxidation-reduction potential (ORP), ammonia, nitrite, nitrate concentrations, temperature, and flow rates. These sensors are linked to supervisory control and data acquisition (SCADA) platforms, enabling operators to visualize system behavior in real time and adjust aeration rates, recirculation flows, and chemical dosing accordingly. In addition to improving responsiveness, these systems reduce manual labor and enhance regulatory compliance by maintaining effluent quality within permissible discharge limits.

Automated feedback loops are particularly effective in controlling DO levels, which are critical for achieving the right balance between nitrification and denitrification or sustaining anammox activity. In aerobic FBRs, maintaining DO within a tight range ensures maximum ammonia oxidation while preventing excessive aeration, which can inhibit downstream processes and waste energy. In hybrid or intermittently aerated systems, real-time control algorithms can dynamically switch between aerobic and anoxic phases based on influent nitrogen concentrations and microbial activity levels (An, Wilhelm & Searcy, 2011; Kandziora, 2019). This approach allows the reactor to self-optimize in response to loading variations, improving stability and nitrogen removal efficiency.

Complementing real-time monitoring, predictive modeling and machine learning (ML) are increasingly being used to enhance process optimization in FBR applications. These tools allow operators and engineers to anticipate performance changes, optimize operational parameters, and detect anomalies before they lead to failures. Predictive models built on historical performance data and operational variables can estimate removal efficiencies, reaction rates, and biomass behavior under different scenarios. This is particularly useful in high-strength wastewater treatment, where influent characteristics are often highly variable and difficult to model using conventional linear equations (An, Wilhelm & Searcy, 2011; Kandziora, 2019).

Machine learning techniques, including artificial neural networks (ANNs), support vector machines (SVM), and decision tree algorithms, have been employed to forecast ammonia and nitrite removal rates, predict biofilm growth dynamics, and estimate microbial population shifts. These models are trained using large datasets generated from FBR operations and can uncover complex, nonlinear relationships between multiple process variables. For example, an ML model can predict when biofilm detachment is likely to occur based on changes in shear stress, nutrient load, and flow regime, allowing for proactive maintenance or adjustments in reactor operation (Yue, You & Snyder, 2014; Oyedokun, 2019). The integration of predictive analytics into control systems enables more robust decision-making and reduces the risk of performance degradation or regulatory non-compliance.

Further innovation is seen in the design of hybrid and modular FBR systems. Hybrid reactors combine the strengths of different biological processes, enabling simultaneous or sequential nitrification, denitrification, and anammox reactions within a single or interconnected unit. These designs are particularly effective for high-strength wastewaters with variable C/N ratios and fluctuating ammonia loads. For instance, a hybrid FBR may contain zones with distinct redox conditions an upper aerobic zone supporting ammonia oxidation and a lower anoxic zone enabling denitrification or anammox (De Almeida, dos Santos & Farias, 2021; Yigitcanlar, Mehmood & Corchado, 2021). Stratification within the biofilm also plays a role, with aerobic microbes such as *Nitrosomonas* and *Nitrobacter* colonizing the outer layers, and anaerobic organisms like denitrifiers or anammox bacteria thriving deeper within the biofilm matrix.

The versatility of hybrid designs allows them to adapt to seasonal changes, diurnal load variations, and shifting influent qualities without extensive operator intervention. In one successful application, a hybrid FBR treating landfill leachate used intermittent aeration to alternate between aerobic nitrification and anoxic denitrification, achieving over 90% total nitrogen removal with minimal external carbon addition. This adaptability not only improves nitrogen removal performance but also reduces energy and chemical inputs, contributing to the sustainability of the treatment process (De Almeida, dos Santos &

Farias, 2021; Yigitcanlar, Mehmood & Corchado, 2021).

Modular FBR systems represent another frontier in innovation. These systems are designed as scalable units that can be deployed independently or in parallel to accommodate varying treatment capacities and objectives. Modular configurations are particularly well-suited for decentralized wastewater treatment in industrial parks, remote agricultural facilities, or emerging urban developments. Each module can be customized for specific treatment goals such as nitrification-only, combined nitrification-denitrification, or anammox-based nitrogen removal depending on the characteristics of the local wastewater stream (Androutsopoulou, et sl., 2019; Kankanhalli, Charalabidis & Mellouli, 2019).

The modular approach also simplifies maintenance and expansion, as individual units can be isolated for servicing or replaced without disrupting the entire treatment process. Furthermore, modular FBRs are ideal platforms for piloting new technologies or microbial consortia in a controlled environment before scaling to full-scale operations. Several commercial FBR systems now offer containerized or skid-mounted units equipped with integrated sensors, PLCs (programmable logic controllers), and telemetry systems for remote monitoring and control, enabling plug-and-play deployment with minimal site preparation.

In addition to technological enhancements, innovations in carrier media have contributed to improved reactor performance. The development of engineered bio-carriers with optimized surface chemistry, shape, and mechanical strength has enhanced biofilm formation, durability, and overall reactor efficiency (Onukwulu, et al. 2021, Taeihagh, 2021). Carriers with internal porosity or surface modifications promote selective colonization by nitrifiers or anammox bacteria, enhancing treatment outcomes. Some FBRs incorporate multiple media types within the same reactor to support diverse microbial communities and allow for flexible operational modes.

The integration of all these advancements real-time sensing, predictive analytics, hybrid designs, and modular architectures represents a transformative shift in how FBRs are conceptualized and applied. These systems are no longer static treatment units but intelligent, responsive platforms capable of adapting to environmental changes, influent variability, and evolving regulatory demands (Standardisation, 2017; Truby, 2020). The result is a new generation of FBRs that are not only more efficient and reliable but also more accessible to a broader range of users, including small-scale industrial operators and developing regions where traditional infrastructure is not feasible.

As the field continues to evolve, future research and development should focus on refining the integration between biological modeling, machine learning, and real-time control to create self-learning, fully autonomous FBR systems. Further exploration into low-cost sensor technologies, energy-efficient aeration strategies, and advanced microbial community engineering will also play a key role in maximizing the potential of FBRs for high-strength nitrogen removal. Ultimately, these innovations will ensure that fluidized bed technology remains at the forefront of sustainable wastewater treatment in the face of growing environmental, economic, and regulatory pressures.

2.7. Challenges and Limitations

Despite the growing recognition of fluidized bed reactors (FBRs) as a promising solution for ammonia and nitrite removal in high-strength wastewater treatment, several challenges and limitations persist that constrain their widespread adoption and long-term operational efficiency. These limitations stem from the intrinsic complexities of biofilm-based systems, the biological and chemical nature of high-strength wastewaters, and the engineering and economic realities of full-scale implementation. Issues such as media clogging and biofilm detachment, extended start-up periods, high energy and operational costs, and difficulties with scalability and sustained performance stability remain critical concerns in both research and practice.

One of the most frequent and disruptive operational challenges in FBR systems is media clogging and uncontrolled biofilm detachment. While the fluidization of media is designed to prevent clogging and encourage uniform mixing, in practice, biofilm overgrowth, accumulation of inert solids, and precipitation of minerals such as calcium phosphate or struvite can lead to media agglomeration (Qrunfleh & Tarafdar, 2014; Wang, et al., 2016). This results in poor fluidization, dead zones within the reactor, and eventually loss of treatment efficiency. Over time, the interstitial spaces between carrier media can become clogged, reducing the effective surface area for microbial activity and impeding mass transfer between the liquid and biofilm interface. This is particularly problematic in high-strength wastewater environments where solids and precipitates are abundant, such as in anaerobic digester effluent or industrial streams rich in organic and inorganic particulates.

Biofilm detachment is another problematic phenomenon, especially under conditions of hydraulic shock or high shear stress. While a certain degree of detachment is necessary to maintain an optimal biofilm thickness and prevent diffusion limitations, excessive sloughing can destabilize the microbial community and result in fluctuations in treatment performance. Detached biomass also increases suspended solids in the effluent, placing an additional burden on downstream processes (Lu, 2019; Simchi-Levi, Wang & Wei, 2018). Achieving a stable balance between biofilm growth and detachment requires precise control of operational parameters such as upflow velocity, aeration rate, and media characteristics something that is not always feasible, particularly in systems dealing with highly variable influent compositions.

Another major limitation associated with FBRs is the long start-up time and the challenges related to microbial acclimatization. Unlike suspended growth systems, where microbial populations can rapidly multiply in the bulk liquid, FBRs rely on the gradual colonization and development of biofilms on the carrier media. This process is time-consuming and sensitive to environmental factors such as temperature, pH, and nutrient availability (Babatunde, 2019; Olukunle, 2013; Danese, Romano & Formentini, 2013). In the context of high-strength wastewater, where influent toxicity and load variability are common, the establishment of a stable and effective microbial community becomes even more difficult. Specific microbial populations such as ammonia-oxidizing bacteria (AOB), nitrite-oxidizing bacteria (NOB), and anaerobic ammonium-oxidizing (anammox) bacteria often exhibit slow growth rates and require carefully managed conditions for successful enrichment.

Start-up periods can range from several weeks to several months, particularly in systems designed for partial nitritation-anammox, where the delicate balance between AOB and anammox populations must be carefully orchestrated. During this phase, system operators often face suboptimal removal efficiencies, the risk of biofilm washout, and the need for repeated seeding or external microbial inoculation. These challenges can significantly delay commissioning timelines and complicate the implementation of FBRs in facilities that require immediate treatment capability (Ijeomah, 2020; Qi, et al., 2017).

Energy and cost considerations further complicate the adoption of FBR technology for high-strength nitrogen removal. Although FBRs are more compact and efficient in terms of biomass retention compared to conventional systems, they often require higher energy inputs for maintaining fluidization, aeration, and internal recirculation. The continuous motion of the media, especially in full-scale reactors, demands reliable pumps and compressors, which increase the energy footprint of the treatment plant (Ochinanwata, 2019; Negi, 2021; Otuoze, Hunt & Jefferson, 2021). Moreover, high aeration requirements to support nitrification or to maintain intermittent aerobic-anoxic zones contribute to operational costs and may reduce the environmental sustainability of the system, particularly in regions with high energy prices or carbon reduction targets.

Capital investment for FBR installation is also relatively high due to the need for durable, specialized media, robust reactor construction, and advanced instrumentation for monitoring and control. Additionally, maintenance requirements for media replacement, sensor calibration, and pump servicing can add to the life cycle costs of the system. While these expenses may be offset by reduced sludge handling or improved effluent quality over time, the initial financial barrier can be a deterrent for small-scale industries or municipal authorities with limited budgets.

Scalability and long-term operational stability represent additional limitations that must be addressed before FBRs can be fully mainstreamed into high-strength wastewater treatment infrastructure. Although laboratory- and pilot-scale studies have demonstrated the effectiveness of FBRs, scaling these systems to full operational capacity introduces new variables that can undermine performance (Akang, et al., 2019; Ezenwa, 2019). Hydrodynamic behavior, mixing efficiency, and oxygen transfer rates do not always scale linearly, requiring detailed engineering adjustments and extensive modeling. Large-scale systems are also more susceptible to spatial variability in biofilm growth, uneven media distribution, and localized clogging, all of which can lead to inefficiencies and inconsistent treatment outcomes.

Operational stability over time is another concern. Biofilm systems, while robust in many ways, are inherently dynamic and subject to shifts in microbial composition, especially under the influence of changing influent quality or temperature. High-strength wastewaters often exhibit wide diurnal and seasonal variability, which can strain the reactor's ability to maintain consistent nitrification and denitrification performance (Kolade, et al., 2021; Ramdoo, et al., 2021). For example, sudden spikes in ammonia concentration or inhibitory substances such as heavy metals or biocides can disrupt microbial activity, leading to process imbalances and effluent non-compliance.

Moreover, maintaining an effective balance between nitrifiers and denitrifiers, or between AOB and anammox bacteria, requires continuous process optimization and operator intervention. In systems where real-time monitoring tools are limited or not integrated with automated control algorithms, the risk of microbial inhibition, biofilm collapse, or process failure increases significantly. Operators must therefore possess a high level of technical expertise and training to manage the complexity of FBR systems effectively, which may not always be available in resource-constrained settings (Adepoju, et al., 2021, Okolie, et al., 2021, Sobowale, et al., 2021).

In summary, while fluidized bed reactors offer substantial advantages for the biological removal of ammonia and nitrite from high-strength wastewaters, several challenges and limitations hinder their universal application. Media clogging, biofilm instability, extended start-up times, high energy and capital costs, and difficulties in scaling and maintaining stable performance represent significant hurdles. Addressing these limitations requires a multi-pronged approach involving the development of more resilient carrier materials, accelerated biofilm start-up techniques, energy-efficient reactor designs, and intelligent control systems. Furthermore, integrating FBRs with upstream and downstream processes in a holistic treatment train can help mitigate some of these challenges and enhance overall system resilience. As research continues to evolve, a more nuanced understanding of microbial ecology, reactor hydraulics, and process economics will be essential in making FBRs a viable, scalable, and sustainable solution for the treatment of nitrogen-rich wastewater streams across various industrial and municipal sectors.

2.8. Conclusion, Future Directions and Recommendations

The systematic review of fluidized bed reactor (FBR) applications for ammonia and nitrite removal in high-strength wastewaters reveals a transformative potential for biological nitrogen management in diverse and demanding wastewater contexts. Across sectors such as landfill leachate treatment, food processing, petrochemical refining, and anaerobic digestion, FBRs have consistently demonstrated high nitrogen removal efficiencies, enhanced biomass retention, and resilience to fluctuating loading rates. By leveraging fluidization principles and biofilm technology, these reactors enable intensified treatment performance within a compact footprint, making them particularly suitable for environments where space, time, or effluent quality standards are critical constraints.

Key findings from this review highlight the advantages of FBR systems in maintaining stable ammonia and nitrite removal, supported by the effective stratification of microbial communities such as *Nitrosomonas*, *Nitrobacter*, and anammox bacteria within dynamic biofilms. The adoption of hybrid and modular reactor designs has further extended the operational flexibility of FBRs, allowing tailored treatment for complex influent characteristics. Real-time monitoring tools and machine learning algorithms now provide the foundation for intelligent, self-optimizing reactor control, improving both efficiency and adaptability. Despite these advancements, operational challenges persist, including media clogging, biofilm detachment, extended start-up times, and cost-related barriers that must be addressed through continued innovation and refinement.

One of the most promising future directions lies in the application of FBRs for decentralized wastewater treatment. Their compact design, ability to operate under varying loads, and potential for containerized, skid-mounted installations make them ideal for remote communities, industrial parks, and decentralized treatment nodes where centralized infrastructure is infeasible. The successful deployment of modular FBR units in such contexts can bridge service gaps, reduce pollution loads on centralized facilities, and promote localized resource recovery, aligning with the broader goals of distributed and circular wastewater management.

To realize the full potential of FBRs, targeted pilot studies and long-term field trials are essential. These studies should focus on evaluating reactor performance under real-world conditions, particularly for emerging high-strength waste streams and low-carbon environments. Long-term assessments will provide crucial insights into operational resilience, maintenance needs, and cost-effectiveness over time, informing design guidelines and regulatory frameworks. These trials should also explore the integration of FBRs into treatment trains that include anaerobic digesters, membrane systems, or advanced oxidation processes to achieve multi-pollutant control and resource recovery.

Critical research gaps remain in the understanding of microbial dynamics and the innovation of carrier media. The biofilm behavior within fluidized systems its composition, thickness, metabolic interactions, and response to stress needs deeper investigation using modern tools such as metagenomics, transcriptomics, and real-time imaging. These insights will inform the development of strategies for selective microbial enrichment, stability enhancement, and biofilm management. Simultaneously, new media materials with improved mechanical strength, anti-clogging properties, and enhanced microbial affinity must be developed to support long-term operation under aggressive wastewater conditions. Biofunctionalized or reactive media that facilitate simultaneous contaminant removal or sensing could also represent the next frontier in FBR development.

Ultimately, the role of fluidized bed reactors in sustainable wastewater management is becoming increasingly vital. As environmental regulations tighten and industries face growing pressure to minimize waste and recover resources, FBRs offer a flexible and effective platform for high-rate nitrogen removal. Their ability to reduce energy demand, minimize sludge production, and support advanced biological processes positions them as a cornerstone technology in the future of ecological sanitation. With continued research, strategic implementation, and policy support, fluidized bed reactors will not only expand their operational footprint but also redefine the benchmarks for efficiency, adaptability, and sustainability in wastewater treatment across the globe.

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