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Research on Efficient Nitrogen Removal Technology in Semiconductor Wastewater

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Abstract:
The semiconductor industry, as the core driver of the digital economy, has brought increasingly severe wastewater treatment challenges as a result of its rapid development. Semiconductor wastewater is characterized by high concentrations of pollutants, complex composition, and high treatment difficulty, especially high nitrogen and high salt wastewater, which puts forward higher requirements for traditional treatment processes. This study focuses on the technical bottlenecks of semiconductor wastewater treatment, and through a combination of literature review and engineering case study, systematically researches the current status and development trend of the application of synergistic denitrification technology in the treatment of semiconductor wastewater, and focuses on the operation mechanism and optimization strategy of the short-range nitrification-anaerobic ammonia oxidation (PN/A) synergistic process. The results show that the synergistic denitrification technology shows significant advantages in semiconductor wastewater treatment: the PN/A combined process can achieve a nitrogen removal efficiency of 92.5% under the condition that the ammonia concentration of the influent water is 380-450 mg/L, and the energy consumption is reduced by more than 60% compared with that of the traditional process.This study not only improves the theoretical system of biological denitrification under complex water quality conditions but also provides an important technical support to promote the green and sustainable development of the semiconductor industry, which is of great theoretical and practical significance to realize the goal of “near-zero discharge” of industrial wastewater.

Keywords: Semiconductor wastewater, nitrogen removal, advanced oxidation, short-range nitrification.

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1. Introduction

In recent years, the semiconductor industry, as the core driving force of the digital economy, has shown explosive growth in its production scale and technology iteration speed. However, behind this rapid development, the complex wastewater problems generated in the semiconductor production process are becoming more and more prominent and have become a key bottleneck restricting the industry's green transformation. Semiconductor wastewater not only contains high concentrations of heavy metals (such as lead, nickel), fluoride and organic pollutants, but also has a high ammonia nitrogen, high salinity and other characteristics, if discharged directly without effective treatment, will seriously damage the ecological balance of the water body, and through the food chain accumulation threat to human health. Although the "Electronic Industry Water Pollutant Emission Standard" (GB 39731-2020) puts forward strict restrictions on wastewater discharge, the traditional treatment process (such as physical precipitation, biochemical treatment) is still faced with high cost, low efficiency, the risk of secondary pollution and other issues, there is an urgent need to develop a new type of high-efficiency, low-carbon, resourceful treatment technology.

Currently, a series of innovative research have emerged in the field of semiconductor wastewater treatment. Le Kaichen for semiconductor plant wastewater characteristics, put forward the classification of collection and quality treatment strategy, through the physical - biochemical - membrane combined process [1] to achieve the efficient removal of heavy metals and organic pollutants, the effluent indexes to meet the standards and the stability of the system is significantly improved; Wang Lichun, etc., as an example of the semiconductor project in Wuxi, Jiangsu Province, to validate the dosing of chemical mixing precipitation, short-range nitrification - anaerobic ammonia oxidation and other processes on mixed wastewater, synergistic treatment efficacy, providing a replicable technology path for engineering practice. Wang Lichun et al. verified the synergistic treatment efficacy of dosing mixed precipitation, short-course nitrification, and anaerobic ammonia oxidation on mixed wastewater, which provided a reproducible technical path for engineering practice. Meanwhile, the anaerobic ammonia oxidation (ANAMMOX) technology has gradually become a research hotspot for the treatment of high ammonia-nitrogen wastewater due to its advantages of autotrophic denitrification, low carbon consumption and low sludge production. Ren Kanghua et al. confirmed that ANAMMOX technology can reduce carbon emission by more than 42% compared with traditional nitrification denitrification process through life cycle assessment (LCA) model, which provides technical support for the industry to achieve the goal of "double carbon"; Du Rui et al. further pointed out that through the short-range nitrification, short-range denitrification and ANAMMOX coupling, it can break through the mainstream municipal wastewater treatment process, which is the best solution for the treatment of high ammonia-nitrogen wastewater. Du Rui et al. further pointed out that through the coupling of short-range nitrification, short-range denitrification, and ANAMMOX, it can break through the bottlenecks of poor adaptability of bacterial strains in mainstream municipal wastewater treatment and low efficiency of nitrogen and phosphorus simultaneous removal, and promote the application of the technology to a wider field. In addition, Qi Yanpei et al. realized the rapid start of short-range nitrification through the strategy of "aerobic aeration + anoxic inhibition" in the treatment of low-ammonia-nitrogen domestic wastewater, which provided a new idea for the nitrogen removal of low-concentration wastewater; and Duan Xiumei et al. constructed the microenvironment of external aerobic and internal anaerobic by immobilizing the nitrifying-ANAMMOX-denitrifying bacteria, which significantly enhanced the ammonia-nitrogen removal efficiency. Which significantly improved the load and stability of ammonia nitrogen removal.

Despite the breakthroughs in process optimization, strain adaptability, and carbon reduction, the complexity of semiconductor wastewater and the fluctuation of water quality still put forward higher requirements for technology integration and system shock resistance. This paper focuses on the semiconductor industry, high ammonia nitrogen, high salinity mixed wastewater treatment problems, to a semiconductor plant in Jiangsu as the research object, to build a "classification collection - physical pretreatment - short-range nitrification - ANAMMOX - depth treatment" of the multi-stage process system [2]. Through pilot experiments to verify the long-term operational efficiency of the process, analyze its technical economy and carbon reduction potential, and explore the synergistic mechanism of bacterial strains and microenvironmental control strategies, aiming to provide a set of solutions for semiconductor wastewater treatment that take into account the efficiency, cost, and sustainability. The subsequent chapters of this paper are organized as follows: Chapter 2 introduces the study area and experimental design, Chapter 3 analyzes the characteristics of wastewater quality and treatment difficulties, Chapter 4 describes the development and optimization of the multistage process, Chapter 5 evaluates the operational efficiency of the process and carbon emission reduction, and Chapter 6 summarizes the results of the research and looks forward to the future direction.

2. Semiconductor wastewater treatment status

2.1 Semiconductor wastewater quality and quantity characteristics

Semiconductor wastewater in terms of water quality and water quantity is showing significant characteristics, these characteristics directly determine the difficulty of its treatment and the choice of technology routes. From the point of view of water quality characteristics, semiconductor wastewater has a high concentration of pollutants, complex composition, mainly manifested as "three high" characteristics: First, high toxicity, wastewater containing copper, nickel, lead and other heavy metals and their complexes, as well as fluoride and other toxic substances; Second, high salt, total dissolved solids (TDS) concentration is usually more than 10,000mg/L; Third, the proportion of difficult-to-degradable organic matter is large, including organic solvents, surfactants, etc. These characteristics require the semiconductor wastewater must take a comprehensive technical route of quality treatment, process coupling, and resource reuse. In the actual treatment process, we need to focus on breaking through the removal of heavy metal complex state, high fluorine/high ammonia and nitrogen degradation, extreme pH regulation and other key technical bottlenecks, in order to ensure that the effluent quality of water to meet the strict requirements of the "Electronic Industry Water Pollutant Emission Standards" (GB39731-2020). From the point of view of water characteristics, semiconductor wastewater is of various types, generating large quantities and significant differences in water quality. According to different production processes, it can be divided into the following categories: fluorine-containing wastewater mainly from the etching and cleaning process; inorganic grinding wastewater generated in the wafer milling process, which contains a large number of suspended particles; organic milling wastewater contains a high concentration of organic pollutants; copper-containing wastewater, nickel-containing wastewater and nickel-containing wastewater containing lead, which mainly comes from the electroplating and metallization process; organic wastewater contains a variety of solvents and detergents; acidic and alkaline wastewater has the characteristics of pH value fluctuations (pH2-12). The water quality and quantity of these wastewaters vary greatly, and it is necessary to establish a perfect diversion collection system to create conditions for subsequent quality treatment. In the actual project, often need to be based on the characteristics of various types of wastewater pollutant concentration and water volume changes, the design of targeted treatment process combinations, in order to achieve cost-effective treatment results.

Taking a semiconductor sealing and testing wastewater project in Jiangsu Province as an example, its wastewater mainly includes fluorine-containing wastewater, inorganic milling wastewater, organic milling wastewater, copper-containing wastewater, nickel-containing wastewater, nickel-lead-containing wastewater, organic wastewater, as well as acid and alkali wastewater, and other types of wastewater. According to the project data, the pollutant characteristics of various types of wastewater are significantly different: the concentration of suspended solids (SS) in inorganic grinding wastewater is as high as 1600mg/L, the chemical oxygen demand (COD) in organic grinding wastewater reaches 1800mg/L, and the total nitrogen (TN) pollution of copper-containing wastewater and nickel-containing wastewater is especially prominent, with concentrations of ≤300mg/L and ≤75mg/L respectively. These high-nitrogen wastewaters will result in water pollution and pollution of the wastewater if they are directly discharged without proper treatment. These high-nitrogen wastewaters, if discharged directly without proper treatment, will lead to eutrophication of the water body, damage to aquatic ecosystems, and enrichment of heavy metals through the food chain, threatening human health.

2.2 Hazards of Semiconductor Wastewater

The hazards of semiconductor wastewater are mainly reflected in three aspects: First, heavy metal pollution, such as copper, nickel, lead and other bioaccumulative, long-term exposure will lead to liver and kidney damage and neurological disorders; second, high concentrations of nitrogen and phosphorus triggered by eutrophication of the water body, resulting in algal outbreaks and the depletion of dissolved oxygen; third, fluoride and organic pollutants on the microbial community to produce inhibition, increasing the difficulty of sewage treatment. Take copper-containing wastewater as an example, its copper ion concentration is ≤30mg/L, far exceeding the limit value of 0.5mg/L stipulated in the Emission Standards for Water Pollutants in the Electronics Industry (GB 39731-2020), and it must be treated in depth by chemical precipitation, ion exchange, and other processes.

2.3 Domestic and international treatment status

From the development trend, China's semiconductor wastewater treatment is developing in the direction of depth, refinement, and resourcefulness. The removal efficiency of characteristic pollutants is enhanced by strengthening the source separation of quality and flow, and optimizing the process combination. At the same time,

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the application of intelligent management and control systems is also gradually promoted. However, compared with the international leading level, there are still gaps in the cultivation of bacterial strains, the popularity of the ZLD system, and the degree of digitization. In the future, it is necessary to strengthen the core technology research, promote the localization of membrane materials, develop biotechnology such as salt-resistant bacterial agents, and establish a better intelligent water management system in order to achieve a synergistic enhancement of environmental and economic benefits. Special attention should be paid to heavy metal recycling, water reuse, and other resource utilization pathways to promote the green and sustainable development of the semiconductor industry.

2.4 New Semiconductor Wastewater Treatment Process

Currently, the semiconductor wastewater treatment field is experiencing a transformation and upgrading from traditional processes to innovative technologies. In the nitrogen removal treatment, has long relied on traditional processes such as A/O method, but these methods have obvious technical limitations: carbon dependence leads to high operating costs, aeration energy consumption accounts for more than 60% of the total energy consumption, while generating a large amount of residual sludge to increase the pressure of disposal, and it is difficult to adapt to the complexity of the semiconductor wastewater water quality characteristics and increasingly stringent requirements for low-carbon emissions. In order to break through these technical bottlenecks, the industry is gradually turning to more efficient, synergistic nitrogen removal processes. In this study, we propose to construct the Anammox - short-range nitrification synergistic system using short-range nitrification to stabilize the supply of nitrite required by Anammox, and at the same time, through the efficient denitrification of Anammox to alleviate the ammonia and nitrogen load of the short-range nitrification reactor, which forms a metabolic complementarity [3]. This synergistic mechanism can significantly reduce the operational energy consumption and the amount of pharmaceutical dosage, providing both efficient and economical solutions for the denitrification of semiconductor wastewater, and helping the electronics industry to green transformation.

3. Potential Advantages of Synergistic Nitrogen Removal Treatment Technology in Semiconductor Wastewater Treatment

Synergistic Nitrogen Removal Technology is a wastewater treatment system that integrates multiple nitrogen removal pathways and processes to form a system with complementary advantages. The core of this technology is to break through the limitations of the traditional single nitrogen removal process and realize efficient and low-consumption nitrogen removal through the synergistic effect of multiple pathways. Its technical connotation mainly includes three aspects: first, metabolic path synergy, through coupling short-range nitrification (PN), anaerobic ammonia oxidation (Anammox), sulfur autotrophic denitrification (SAD) and other different nitrogen removal pathways, to build a flexible treatment system adapted to different water quality conditions; second, physical-chemical-biological synergy, advanced oxidation, electrochemical assisted and other physicochemical methods organically combined with biological treatment; third, functional The third is functional bacterial synergy, through the construction of special microbial communities to achieve functional complementarity, such as ammonia oxidizing bacteria and anaerobic ammonia oxidizing bacteria synergistic effect.

Synergistic nitrogen removal technology has significant advantages in treating semiconductor wastewater [4]. Firstly, it has outstanding anti-salt inhibition ability, and can tolerate the wastewater environment with TDS as high as 30g/L by enriching salt-tolerant bacterial populations and optimizing process parameters. Secondly, the operating cost is greatly reduced, for example, the PN/A process can save 60% of the aeration energy consumption and 100% of the external carbon source demand compared with the traditional nitrification process. Furthermore, the technology has the potential for resource recovery, which can realize the simultaneous recovery of various resources such as nitrogen and sulfur. In addition, its treatment efficiency is significantly improved, and it has a unique advantage for wastewater with a low carbon to nitrogen ratio (C/N<3), and the nitrogen removal load can be up to 2-3 times of the traditional process.

At present, this technology has been successfully applied in several semiconductor wastewater treatment projects. Peng Yongzhen team of Beijing Institute of Technology in a semiconductor enterprise to implement the demonstration project shows that the use of short-range nitrification - anaerobic ammonia oxidation (PN / A) combination of processes to treat wastewater containing nitrogen, the influent ammonia nitrogen concentration of 380-450mg / L, C / N ratio of <2.5 under the conditions of the denitrification efficiency of 92.5%, the energy consumption of only 0.8kWh / kgN, compared with the traditional process to reduce 62%. The sulfur autotrophic-electrochemical synergistic system (SAD-MFC) developed by the School of Environment, Tsinghua University, treats high-sulfate wastewater with a TN removal load of $0.4kgN/(m^3\text{-}d)$, while realizing a power production density of 0.8W/m³, and can tolerate a high-salt environment of 10g/L NaCl. The salt-tolerant Anammox-MBR system designed by the Ecology Center of the Chinese Academy of Sciences operates stably in the salinity range of 5-20g/L, with the nitrogen removal efficiency maintained above 80% and the membrane contamination cycle extended to 45-60 days.

These project cases show that synergistic denitrification technology provides an efficient and economical solution for semiconductor wastewater treatment through the innovative mode of "multi-path complementary, physical-chemical-biological linkage, and salt-resistant resource utilization". In the future, with the cultivation of salt-resistant bacterial agents, intelligent control, and other technological breakthroughs, this technology is expected to become the core process for realizing the goal of "zero discharge" of semiconductor wastewater, and to promote the green and sustainable development of the semiconductor industry.

4. Synergistic mechanism of anaerobic ammonia oxidation and short-range nitrification

4.1 Reaction mechanism of anaerobic ammonia oxidation (Anammox) process

Anaerobic ammonia oxidation (Anammox) process is a highly efficient biological nitrogen removal technology [5], and its reaction process can be divided into two key stages: firstly, partial nitritation (PN), which converts about 55% of the ammonia nitrogen into nitrite nitrogen; subsequently, under anaerobic conditions, the remaining ammonia nitrogen is converted into nitrous nitrogen as an electron acceptor through anaerobic ammonia oxidation bacteria directly into nitrogen, and this complete process is known as the PN/A process.

The Anammox-UASB (Upflow Anaerobic Sludge Bed) system is a typical reaction unit for this process, which consists of three functional units: the influent unit conveys the mixed wastewater containing NH_4^+-N and NO_2-N to the reactor through an influent pump, and is equipped with a heating rod to maintain the optimal reaction The reaction unit adopts the UASB configuration, whose special three-phase separation structure and sludge bed design provide an ideal growth environment for anaerobic ammonia oxidizing bacteria; the effluent unit partially reflows the mixture containing residual NO_2-N and NH_4^+-N through a return pump, which optimizes the reaction conditions and optimizes the flow back to the reactor. Reflux, which both optimizes the reaction conditions and improves the nitrogen removal efficiency. This recirculation design enables the system to stably maintain the C/N ratio and pH value, and the total nitrogen removal rate can reach more than 80% under the typical working condition, which is especially suitable for the treatment of semiconductor wastewater with high ammonia-nitrogen and low carbon/nitrogen ratio.

The core advantage of this system is the integration of the two reaction stages, PN and Anammox, in a single reactor and the synergistic effect of nitrifying bacteria and anaerobic ammonia-oxidizing bacteria by controlling the dissolved oxygen (DO<0.5mg/L) and reflux ratio (usually 30-50%) [6]. The NO_2-N/NH_4^+/NH_4-N ratio (the theoretical optimum value is 1.32:1) and sludge properties (typical particle size 0.5-1.0 mm) need to be monitored in actual operation, which directly affect the nitrogen removal efficacy and system stability.

There are two main technological pathways for oxidative nitrogen removal by aerobic ammonia(Fig.1). Under aerobic conditions (pathway 1), NH_4^+-N is partially oxidized to NO_2-N by short-range nitrification; under anoxic conditions (pathway 2), NO_2-N is oxidized to N_2 by an anaerobic ammonia oxidation reaction, with the remaining NH_4^+-N through anaerobic ammonia oxidation reaction to produce N_2 directly. Meanwhile, the presence of COD and O_2 in the system affects the reaction process, while NO_3-N is produced as a by-product. The whole process reflects a complete conversion pathway from ammonia to nitrogen, highlighting the synergistic effect of short-range nitrification and anaerobic ammonia oxidation.

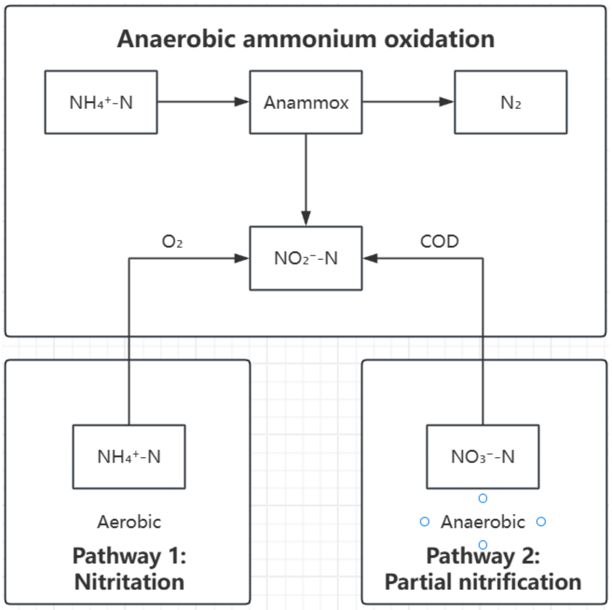

Fig.1 Two main technological pathways for the oxidative denitrification of oxygen and ammonia

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4.2 Biochemical processes and regulation of short-range nitrification

Short-range nitrification technology is a biological denitrification process that converts ammonia and nitrogen mainly into nitrite without generating nitrate by precisely controlling the reaction conditions. Its core is to create an environment suitable for the growth of ammonia oxidizing bacteria (AOB) and inhibit the activity of nitrite oxidizing bacteria (NOB): control pH at 7.5-8.5, temperature 30-35 ℃, dissolved oxygen 0.3-0.5 mg / L, and use the selective inhibition of free ammonia and free nitrite. The process can convert more than 80% of ammonia nitrogen into nitrite, providing an ideal substrate for subsequent anaerobic ammonia oxidation with low energy consumption and high efficiency, especially suitable for treating wastewater with low carbon-to-nitrogen ratio. The key to successful operation lies in the precise regulation of reaction conditions and the stable management of the system.

4.3 Reaction mechanism of anaerobic ammonia oxidation (Anammox) process

The PD-A process combines nitrification, short-range denitrification, and anaerobic ammonia oxidation reactions. Theoretically, 55% of NH_4^+ is oxidized to NO_3- by nitrifying bacteria, and NO_3^- undergoes a short-range denitrification reaction to produce NO_2- by denitrifying bacteria, and NO_2^-does not continue to reduce to N_2, but reacts with the remaining NH_4^+ in the raw water as a substrate for the anaerobic ammonia-oxidizing bacteria to produce N_2.

The PD-A process has a lower operating cost than the conventional nitrification-denitrification process. Theoretically, to remove 1 mol of NH_4^+, the conventional nitrification-denitrification process needs to consume 2 mol of O_2 and 5 mol of electron donor, while the PD-A process only needs to consume 1.1 mol of O_2 and 1.1 mol of electron donor. Therefore, the PD-A process can reduce the oxygen consumption by 45% and the carbon source requirement by 78% compared to the conventional nitrification-denitrification process.

The PD-A process operates stably, with a total nitrogen removal rate of up to 100% theoretically, and can reduce the production of the greenhouse gas N_2O. Short-range denitrification uses organic matter as the carbon source to achieve the removal of organic matter, and when the influent water quality fluctuates, the system can maintain its stability of the system through denitrification and anaerobic ammonia oxidation. The small amount of NO_3^- produced by the anaerobic ammonia oxidation reaction is further reduced to NO2⁻ by short-range denitrification, which provides substrate for the anaerobic ammonia oxidation reaction, which improves the total nitrogen removal rate of the system. In addition, the reduction of NO_3^- to NO_2^- in the conventional denitrification process produces N_2O byproducts, whereas the PD-A process cuts down the production of N_2O.

There are 2 types of PD-A process, one integrated type and split type. Short-range denitrification and anaerobic ammonia oxidation reaction in the same reactor is integrated type, short-range denitrification and anaerobic ammonia oxidation reaction in different reactors is split type, as shown in Fig.2.

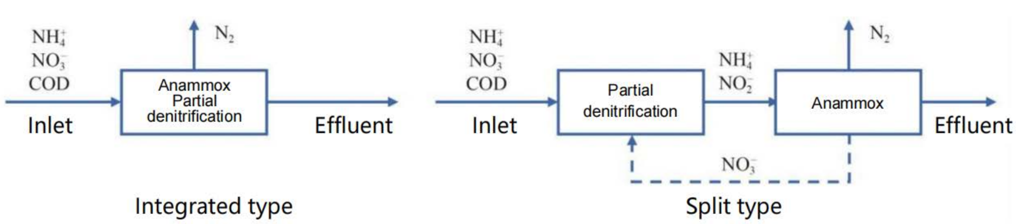

Fig.2 One-piece and split PD-A process

4.4 Process optimization and control strategies

The optimization and regulation of anaerobic ammonia oxidation denitrification process is currently an important research direction in the field of wastewater treatment. In practical engineering applications, the technology faces multiple challenges: toxic substances in industrial wastewater can significantly inhibit the activity of anaerobic ammonia oxidizing bacteria, fluctuations in water quality can easily lead to an imbalance in the short-range nitrification process, and traditional control methods are difficult to cope with dynamic load changes. These problems directly affect the denitrification efficiency of the system, usually resulting in 20-30% performance fluctuations, while leading to insufficient operational stability, with the mean failure interval often less than 60 days. These technical bottlenecks have severely restricted the large-scale application of the anaerobic ammonia oxidation process, so there is an urgent need to optimize the process through technological innovation.

In terms of anaerobic ammonia oxidation technology enhancement, strain engineering is the key breakthrough.

The activity of the bacterial colony can be enhanced by more than 40% through anticorrosive domestication techniques, such as gradient salinity acclimatization training, combined with polyvinyl alcohol gel carrier immobilization technology. Especially for heavy metal pollution in semiconductor wastewater, the development of genetically engineered bacteria resistant to heavy metals such as copper and nickel is particularly important. Process coupling is another important direction. When constructing a sulfur-anaerobic ammonia oxidation synergistic system, controlling the sulfur-to-nitrogen ratio in the range of 2.8-3.2 or adopting an electrochemical auxiliary device to maintain the cathodic potential at about -0.3V can significantly enhance the system's ability to treat complex wastewater. The intelligent control system adopts a machine learning-based dissolved oxygen regulation model, with a control accuracy of ±0.1mg/L. Together with an online ammonia nitrogen/nitrite monitoring system with a response time of less than 5 minutes, it realizes real-time optimization of process parameters. In terms of resource utilization, the supporting ammonia blow-off recovery system can achieve more than 85% ammonia recovery rate, while reducing the carbon footprint by 30%.

The stability enhancement of short-range nitrification, as the key link of anaerobic ammonia oxidation in the front, is crucial. Through intermittent aeration control, the cycle mode of 3-minute aeration and 7-minute stopping aeration is used to maintain the free ammonia concentration at 0.5-1.0 mg/L, which can effectively inhibit the activity of nitrite oxidizing bacteria. In order to cope with the fluctuation of COD in the influent water, a buffer tank with a hydraulic retention time of not less than 2 hours is set up, and with activated carbon adsorption pretreatment, which can significantly improve the system's ability to resist shock load. The pH-ORP linkage control strategy is adopted to automatically adjust the aeration volume when the pH inflection point exceeds 7.6, which can ensure the stable operation of the short-range nitrification process.

In the optimization of PD-A synergistic process, carbon source regulation is the key. The COD/NOx-ratio was controlled in the range of 2.5-3.0, and sodium acetate was preferred as the carbon source, whose denitrification rate was 20% higher than that of the traditional methanol carbon source. The sludge inoculation adopts the compound inoculation of 30% aerobic nitrifying sludge and 70% anaerobic granular sludge, which can accelerate the symbiosis of functional flora. For the optimization of process parameters, the dissolved oxygen was controlled in the range of 0.3-0.5 mg/L, and the temperature was maintained at 32±1℃, which could achieve more than 80% nitrite accumulation rate.

The future direction of development should focus on the development of modularized equipment, the development of containerized treatment units with a treatment capacity of no less than 5 m3/hour, and the formulation of technical specifications covering the entire process of design, operation and monitoring. Through the above optimization measures, it is expected that the system's shock load resistance can be increased by 50%, and the operational energy consumption can be reduced by 35%, thus promoting anaerobic ammonia oxidation technology to become the mainstream nitrogen removal solution, and providing a more efficient and economical process option for industrial wastewater treatment. These technological innovations will not only solve the current technological bottlenecks, but also make an important contribution to the sustainable development of water pollution treatment.

5. Future outlook

PD-A process (short-range denitrification-anaerobic ammonia oxidation), as a new wastewater treatment technology with the advantages of low cost, easy operation and high efficiency of nitrogen removal, is regarded as an important development direction in the field of nitrogen removal in the future. However, the current research mainly focuses on the laboratory stage, mostly using methanol, sodium acetate and other single carbon source of artificial water distribution for testing, and the actual semiconductor wastewater there are significant differences - the real wastewater not only contains fluoride, heavy metals and other complex components, but also face the challenge of water quality fluctuations, resulting in the engineering application of the process is relatively limited. limited. In view of these bottlenecks, future research should focus on three core directions: firstly, we need to carry out actual wastewater validation tests to systematically assess the treatment efficacy of the PD-A process on real semiconductor wastewater, focusing on water quality fluctuations, low-temperature environments, and inhibition of toxic substances and other engineering challenges; secondly, we need to explore the synergistic symbiotic mechanism of anaerobic ammonia-oxidizing bacteria and denitrifying bacteria, and optimize the structure of bacterial colony to enhance system stability; finally, we should develop a smart control mechanism to regulate and control the water quality. Finally, an intelligent control system should be developed to dynamically adjust the denitrification mode based on real-time monitoring of nitrate concentration data, such as switching to sulfur autotrophic denitrification and other alternate processes under specific conditions, so as to ensure that the treatment system can maintain high efficiency and stable operation under different working conditions [7]. These research breakthroughs will promote

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the PD-A process from the laboratory to the engineering practice, for semiconductor wastewater treatment to provide more cost-effective solutions.

6. Conclusion

This study systematically explores the current status and development prospect of synergistic nitrogen removal technology in semiconductor wastewater treatment, focusing on the synergistic mechanism of anaerobic ammonia oxidation (Anammox) and short-range nitrification (PN) and their engineering applications. The technical advantages, operation mechanism and optimization strategy of PD-A process (short-range denitrification-anaerobic ammonia oxidation) in semiconductor wastewater denitrification treatment were investigated by combining literature review and case study.

It was found that the synergistic denitrification technology showed significant advantages over the traditional process: in terms of technical performance, the combined PN/A process can achieve 92.5% nitrogen removal efficiency with energy consumption as low as 0.8kWh/kgN; in terms of economics, it saves 60% of the aeration energy consumption and 100% of the demand for external carbon source; in terms of adaptability, the salt-resistant Anammox-MBR system can be stably operated in the range of 5-20g/L salinity range. The study also revealed the control points of key process parameters, such as maintaining DO at 0.3-0.5mg/L and temperature control at 32±1℃, which can achieve more than 80% nitrite accumulation rate. Through the construction of "metabolic pathway synergy - physical and chemical biological coupling - intelligent regulation" technology system, effectively solved the semiconductor wastewater high salt inhibition, insufficient carbon source and other engineering challenges.

Looking ahead, the research in this field should focus on three directions: first, strengthening the actual wastewater validation, focusing on the breakthrough of heavy metals, fluoride and other complex components of the inhibitory effect; second, deepening the study of microbial mechanism, through genetic engineering to cultivate toxin-resistant strains of bacteria; and third, to promote the upgrading of the intelligence, and the development of accurate control system based on the digital twin. The practical significance of this study is to provide the semiconductor industry with both efficient and economical wastewater treatment solutions, and to promote the green transformation of the electronics manufacturing industry; its theoretical value is reflected in the improvement of the synergistic mechanism of biological denitrification under complex water quality conditions, and to provide a new way of thinking for the technological innovation of water treatment. Through continuous optimization and engineering promotion, the synergistic nitrogen removal technology is expected to become the core supporting technology to achieve the goal of "near-zero discharge" of industrial wastewater.

References

[1] REN Kanghua,LIAO Yufeng. Operational effectiveness analysis and carbon emission assessment during anaerobic ammonia oxidation treatment of high ammonia-nitrogen wastewater[J/OL]. Cleaning World,1-6[2025-07-10].http://kns.cnki.net/kcms/detail/11.4834.tq.20250625.0845.008.html.

[2] DU Rui,XU Xinyi,XU Xinyi,et al. Progress of simultaneous nitrogen and phosphorus removal from wastewater by a novel anaerobic ammonia oxidation process[J/OL]. Journal of Beijing Institute of Technology,1-18[2025-07-10].http://kns.cnki.net/kcms/detail/11.2286.t.20250604.1044.002.html.

[3] QI Yanpei, PANG Suyan, ZHANG Gan, et al. Efficacy of short-course nitrification-anaerobic ammonia oxidation process for the treatment of low ammonia-nitrogen domestic wastewater[J]. Environmental Science and Technology,2025,38(02):35-40.DOI:10.19824/j.cnki.cn32-1786/x.2025.0026.

[4] Le Kaichen. Design and application of a semiconductor plant production wastewater fractionation treatment process[J]. Cleaning World,2025,41(01):49-51.

[5] Deng Kaili, Xing Wei, Cao Enkai, et al. Analysis of the operational efficiency and carbon emission of anaerobic ammonia oxidation for the treatment of high ammonia-nitrogen wastewater[J]. Industrial Water Treatment,2025,45(04):169-175. DOI:10.19965/j.cnki.iwt.2024-0301.

[6] Xumei Duan,Xin Yin,Jiewen Leng,et al. Co-embedded nitrosation-anaerobic ammonia oxidation-denitrifying bacteria immobilization for the treatment of ammonia-nitrogen wastewater[J]. Water Treatment Technology,2024,50(08):110-114.DOI:10.16796/j.cnki.1000-3770.2024.08.019.

[7] WANG Lichun,XU Wenxiang,ZHANG Yumeng,et al. Example of a new process to treat wastewater from semiconductor industry[J]. Shanxi Chemical Industry,2023,43(09):234-236.DOI:10.16525/j.cnki.cn14-1109/tq.2023.09.093.