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Sustainable approach of biological treatment of landfill leachate by Anaerobic Ammonium Oxidation: A review

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Abstract. An upsurge in living standards, rising industrialization and urbanization, the protection of water environment has become a priority. Anaerobic ammonium oxidation process has drawn a lot of attention since it demonstrated substantial advantages over conventional nitrogen removal techniques, including a 100% reduction in the amount of organic carbon required, a 60% reduction in the amount of aeration needed, and a 90% reduction in the amount of sludge produced. Effective treatment of landfill leachate is extremely important as leachate is a threat to the environment. Municipal waste management is still a challenging situation in developing countries. Uncontrolled waste disposal results in greenhouse gases emissions which worsens climate change as the leachate will pollute water bodies, soil and a significant air pollution which impacts on human health will be released. This paper reviewed several published research works in Scopus dealing with the leachate treatment by Anammox process combined with some other systems and highlighted some common challenges found with the application of this new technology. Treating landfill leachate resulted in an excellent ammonium NH_4^+-N removal efficiency. However, it has been highlighted that most of the research reviewed reported some limitations of the technology on a small scale such as the low start-up time affecting the growth of bacteria in the reactors and the instability of the system when pH and temperature decrease. Biological treatment, Anammox method included, offers a cost-effective, eco-friendly, and an effective solution for nitrogen removal.

Key words: Landfill, leachate, Anammox, Nitrogen removal

1. Introduction

Today, the world is marked by a major environmental crisis, which has been triggered by the inadequately discharge of untreated wastewater resulting from the rapid expansion of industrialization and urban development. Wastewater treatment is a strategy that improves the wastewater's quality so that it can be suitable for drinking or for other uses. The aim of wastewater treatment is to eliminate or significantly reduce pollutants from the wastewater that, if discharged into surface and/or ground waters without appropriate treatment, constitute hazards to people's health and the environment [1–3].

The protection of the environment has become a priority trend because of the advancement of economic growth and quality of life, together with the rising amount of industry and urbanization. The activated sludge technique is employed during wastewater treatment to facilitate the breakdown of abundant organic matter into CO_2, accomplished through the utilization of microorganisms and an aeration mechanism. This procedure requires a considerable amount of energy, especially from the aeration systems [4–6].

Leachate is a word that is frequently used in environmental sciences and is one of the various effects of this process. It refers to a polluted liquid that is frequently produced when water percolates from a solid waste disposal site and has components that are hazardous to the environment. The components of leachates from landfills vary widely depending on how long the dumpsite has been in operation [7–9]

Leachate from inadequate landfill management has been identified as the primary cause of hydrogeological pollution, which seeps into the groundwater and soil. Furthermore, humic acids, xenobiotic organic compounds (XOCs), ammonia nitrogen, heavy metals, and various inorganic salts are among the high-strength organic and inorganic pollutants that make up leachate [10–12].

In several countries around the world, landfills continue to be a popular and economical method of managing municipal solid waste. However, non-engineered waste disposal facilities provide significant risks to groundwater due to biological, chemical, or physiochemical processes, as well as the potential release of volatile gases into the surrounding environment [13].

Considering removing nitrogen and organic matter from sewage is crucial to mitigating water contamination, several nations have recently implemented rigorous wastewater discharge regulations. Many landfills in developing countries are inadequately engineered, which makes it difficult to convert waste materials into lucrative products that can be marketed. There is a commitment to implementing treatment facilities that encourage resource recovery [1,14].

Leachate has been treated using a variety of physicochemical techniques, including coagulation-flocculation, adsorption, membrane filtering, ozonation and sophisticated oxidation procedures. A noteworthy proof of high efficiency attained by combining physicochemical and biological mechanisms for nitrogen removal in landfill leachate has been made in the last few years. The identification of an optimal approach for the treatment of leachate remains a significant obstacle in current research and practice [15]. Nitrogen contamination, or the presence of nitrogen in water bodies, may lead to significant problems such river eutrophication, poorer quality of water, along with potential health risks for people and animals. It is necessary to provide treatments prior to the direct discharge of the substance into the receiving bodies of water. Anammox is an identified technique for biological nitrogen removal from wastewater that is doable, energy-efficient, and shows potential. The conventional nitrogen removal technology produces more CO_2 emissions, sludge, and demands more oxygen than the Anammox process [16,17].

The Anammox method has been widely investigated for the purpose of nitrogen removal from landfill leachate, due to its remarkable effectiveness. The method in question exhibits reduced operation costs and generates a lesser amount of waste sludge in comparison to alternative approaches, attributable to its lower waste sludge output and cost-effectiveness. Since it does not need on oxygen, this method exhibits reduced energy consumption, hence resulting in less environmental impacts as compared to conventional approaches and it is considered as an innovative biological method for wastewater treatment [18]

Leachate is unavoidably produced in significant amounts during the incineration, landfilling, and composting processes, amounting to 5.0%–28.0%, 4.0%–50%, and 4.0%–26.7% of the volume of solid waste, respectively [19]. The focus of this work is to give a comprehensive understanding of the various descriptions of Anammox and several methods and coupled systems used for nitrogen removal in landfill leachates. This research provides a review of the prevalent challenges encountered by various systems when paired with Anammox for enhancing nitrogen removal efficiency.

2. Methodology

The methodology employed in this study is derived from the scoping review process established. Google Scholar, Web of Science, and Scopus are frequently used databases for academic publications. Scopus is often regarded as an excellent option due to its extensive coverage of bibliometric data. Nearly all of the articles reviewed in the context of Anammox research used the Scopus database as their primary platform for publication. Therefore, the Scopus database was selected as the designated instrument for data retrieval in this study. A set of inclusion and exclusion criteria was created in order to filter journal articles that are not relevant to the current inquiry. The researchers established the criteria for eligibility, identified the sources of information, and formulated the tactics for conducting the search (see Table 1). The research utilised certain search keywords, including "landfill leachate," "leachate," "Anammox," "nitrogen removal," "anaerobic ammonium oxidation," and "biological treatment," to perform the investigation. The research was conducted in English.

Table 1:Inclusion criteria used to exclude unnecessary journal articles and reviews.

Sorting option	*Criteria applied*
Publication date	2019-2023
Source type	Journal
Document type	Review, article
Availability	Full text, open access

3. Results and discussion

This section describes the systematic literature review of identified key parameters related to Anammox process for treating landfill leachate.

3.1 Anaerobic ammonium oxidation process

The Anammox process is a two-stage system used for the removal of nitrogen from wastewaters. The first phase involves partial nitrification, during which about 50% of the NH_4^+ ions are oxidized to NO_2. The second step, known as the Anammox process, occurs under anoxic conditions and involves the oxidation of NH_4^+ ions with NO_2^- to produce N_2 gas [20,21].

The process of anaerobic ammonium oxidation involves the conversion of ammonium, acting as an electron donor, and nitrite, serving as an electron acceptor, into nitrogen gas. This transformation occurs in the presence of carbon dioxide (CO_2), which serves as the carbon source necessary for the development of the Anammox bacteria (see Eq. 1) [22].

$$NH_4^+ + 1.3H^+ + 1.32NO_2^- + 0.06HCO_3^- \rightarrow 1.02N + 0.26NO_3^- + 2.03H_2O + 0.06CH_2O_{0.5}N_{0.15} \quad (1)$$

[23] It has been suggested that to optimize the use of scarce resources, it is possible to implement procedures that facilitate the recovery and recycling of nutrients found in sewage, so minimizing any potential harm to the environment.

The broader picture of sustainable development, considering environmental, economic, and social factors, should be considered while designing an effective framework concept for waste management. The Anammox process has garnered considerable interest because to its demonstrated advantages over conventional methods for nitrogen removal, including a 100% reduction in the amount of organic carbon required, a 60% reduction in the amount of aeration needed, and a 90% reduction in the amount of sludge produced. In the past few years, it has been as well thoroughly explored for prospective engineering applications as an alternative for nitrogen removal techniques [24].

With an attractive application, this bacterial process, which has been demonstrated to be a budget-friendly and highly efficient wastewater treatment method, has drawn a lot of interest. Nitrite (NO_2) is reduced to nitrogen gas (N_2) via the Anammox process[25], using ammonium (NH_4^+) as the electron donor [26,27]. However, ensuring both the maintenance and improvement of stability and optimal efficiency in the Anammox process are crucial factors in the advancement of carbon-neutral wastewater treatment facilities [28].

The conversion of biologically accessible nitrogen molecules like ammonium, nitrite, or nitrate to elemental nitrogen (N_2), which is let out into the natural environment as a harmless byproduct [29], is usually taken as nitrogen elimination. Ammonia stripping and chemical precipitation are two examples of physical-chemical processes for nitrogen removal that have high operating costs and considerable chemical requirements. In contrast, biological processes remove organic carbon and nitrogen more effectively and at a lower cost [30,31]. Nevertheless, there are fewer economic benefits and a possibility of secondary contamination associated with traditional nitrification and denitrification processes, which need significant oxygen supply and organic carbon supply.

In the Anammox process, nitrite and ammonium ions are immediately converted to diatomic nitrogen and water. Anammox is a globally important nitrogen cycle microbial process that occurs in a variety of natural environments [26,32]. The application of Anammox in urban wastewater systems has the potential of optimizing energy recovery by redirecting organic carbon from the nitrogen removal process and redirecting it towards anaerobic digestion. This phenomenon occurs due to the autotrophic nature of Anammox bacteria [33]. The actual implementation of Anammox systems at pilot and industrial sizes is challenging due to the dependence of nitrogen removal efficiency and Anammox activity in landfill leachate treatment on many operational factors [34]. The vulnerability of Anammox bacteria to non-essential inhibitors, such as sulphides, toxic metal ions, alcohols, and antibiotics, may be attributed to the variability of the wastewater composition [4,35].

With the train that global warming takes, we all run behind every possibility to live well in harmony with nature and above all to help it to regenerate by minimizing all possible risks. Handling waste is one step, reusing it and recycling it is another step. But processing the last debris before putting it to its final disposal before nature takes care of it is a big step. This study provides an overview of landfill leachate treatment methods that effectively mitigate the hazards of surface and groundwater contamination. Numerous research studies have been conducted in this field to explore strategies that lessen the associated consequences and costs of such treatment processes. With appropriate management and treatment of the effluent prior to its disposal in compliance with environmental regulations, other technologies paired with Anammox can be used for mature landfill leachate treatment, providing the limitations of one to be resources or raw materials for another.

3.2 Anammox bacteria

There are six types of Anammox bacteria that have been discovered and identified: *Brocadia, Kuenenia, Jettenia, Scalindua, Anammoxoglobus,* and *Anammoximicrobium*. The order Planctomycetales is home to all recognized kinds of Anammox. *Scalindua* is a rare instance and is frequently identified in marine sediments [36,37].

[38] investigation demonstrated that the proportion of *Brocadia* and *Kuenenia* in the suspended sludge during the early stages was notably elevated, accounting for 7.7% and 6.9% respectively. The injection of seawater led to a significant decrease in the overall percentage of *Brocadia* to 2.1%, whereas the relative abundance of *Kuenenia* increased to 14.4%. This alteration matches with the observed higher tolerance of *Kuenenia* to salinity. *Candidatus Brocadia* was found to be the primary species of Anammox in most leachate treatment facilities, especially those that used partial nitrification and denitrification with Anammox [39].

3.2.1 Performance of the Anammox bacteria in some combined technologies

The Anammox bacteria play a major part in enhancing the efficiency of nitrogen removal in Anammox techniques. Still, [40] has been demonstrated, microbial interactions or competitiveness in Anammox consortia may alter nitrogen removal efficiency. Meaning that the occurrence of sludge formation or the efficiency of the reactor may not always be entirely dependent on the presence of the Anammox bacteria. Because Anammox process theoretically produces 11% more nitrate than it consumes, nitrate is the predominant nitrogen substrate that limits the efficiency of nitrogen removal.

The catabolic processes regarding Anammox bacterial cells are carried out in the Anammoxosome, an intra-cytoplasmic division that produces a proton gradient throughout its membrane [36]. [27]findings indicate that the accumulation and adaptation of Anammox biomass may occur effectively, even under prevailing conditions characterized by a nitrogen concentration of around

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30 mg N/l and a temperature of approximately 20°C. The findings of the study clearly revealed that Anammox bacteria have the potential to exhibit strong activity and a high rate of development even when exposed to low levels of substrate concentration within the temperature range of 15-20°C. Anammox bacteria have been shown to be present in all conventional full-scale municipal WWTP. Still, the use of this technology in wastewater treatment facilities presents difficulties due to the limited availability and sensitivity of Anammox bacteria to many environmental factors, including high levels of dissolved oxygen (DO) and organic carbon [40,41].

[42] found that the presence of in situ enriched Anammox bacteria was observed in the anoxic zone. Notably, the abundance of these bacteria was found to be considerably greater than the reported values observed in conventional wastewater treatment plants. The ultimate stage encompasses the process of oxidizing hydrazine to dinitrogen gas via the enzyme hydrazine dehydrogenase (Hdh) [36]. [42] study showed that the integration of denitrification and Anammox processes using anoxic carrier biofilms has significant promise for improving nitrogen removal in continuous flow municipal wastewater treatment plants. In the anoxic zone, biofilms may in fact boost Anammox bacteria. The process of nitrate reduction can serve as a framework for the gradual accumulation of Anammox bacteria in anoxic-carrier biological films, which are distinguished by low levels of dissolved oxygen and longer periods of solid retention time. Additionally, nitrate reduction facilitates the proliferation and dispersion of Anammox bacteria inside these biofilms. The findings of their study indicated that the anoxic carrier biofilms had a positive contribution to the process of nitrogen removal. Furthermore, the anaerobic zone exhibits comparable environmental parameters, such as matrix conditions, dissolved oxygen levels, and temperature [43].

[40] provided evidence that microbial interactions play a crucial role in facilitating the fast development of Anammox sludge and the creation of biofilms. The results of their study underscored the significance of using inoculated Anammox consortia in the context of Anammox engineering applications. [44] reported that the microalgae and bacteria may cohabit in a wastewater treatment system under suitable environmental conditions, and a wide range of bacterial species can form granules with microalgae. Both Anammox bacteria are autotrophic microorganisms that produce very little biomass and have extremely slow growth rates. Thus, the partial nitritation-Anammox process' ability to operate steadily depends on effective sludge retention.

3.3 Treatment of Landfill leachates by Anammox process

It is imperative that we deal with the increasing amount of Municipal Solid Waste in a sustainable manner to tackle the expanding environmental, economic, and social problems. Two commonly used methods for disposing of waste are landfilling (because it is inexpensive and simple to operate) and incinerating (because there is a shortage of land for new landfill sites). However, the effectiveness of these techniques has been questioned due to the emission of hazardous chemicals and gaseous pollutants, prompting the implementation of stringent restrictions aimed at protecting the environment and human health [45]. The degree of pollution caused by these substances is regarded to be high. But the composition of landfill leachate can vary considerably. Some of the physiochemical parameters of landfill leachate are given in Table 2 based on the report of [22].

Table 2:Typical physiochemical parameters of landfill leachate [22]

Parameter	Range (mg/L)
pH [a]	4.5-9.0
Total solid	2000-60,000
Biological Oxygen Demand (BOD)	20-57,000
Chemical Oxygen Demand (COD)	140-152,000
BOD/COD (ratio)	0.02-0.80
Total organic carbon (TOC)	30-29,000
Organic nitrogen	14-2,500
Ammonium-N	100-5,500

With early aerobic landfilling, concentrations of organic components in leachate (e.g., BOD5>3000 mg/L and COD>6000 mg/L) can be extremely high. During the methanogenic phase, these concentrations drop and stabilize [46]. They presented data on the concentrations of common compounds found in landfill leachate (see Table 3). Some data are missing due to insufficient literature. The chemical characteristics of leachate exhibited significant variations across different climatic zones and landfill ages.

The removal of a wide variety of pollutants and the need for the use of advanced technologies make the treatment of landfill leachates a challenging problem. Nitrogen should be treated as the top priority when it comes to landfill leachates because of the high levels of ammonium in the leachate.

Landfill leachate exists as young (BOD_5/COD ≥0.6), middle (0.1-0.6), and mature leachate (≤0.1). The BOD_5/COD ratio of young leachate is elevated, and it typically comprises biodegradable organic compounds. In contrast, adult landfill leachate consists of permanent organic compounds that provide challenges for elimination. Landfill leachate has significant quantities of NH_4^+-N, organic molecules such as pesticides and humic acid, inorganic pollutants, heavy metals, and substances with carcinogenic properties [47,48]. [49] The removal of nitrogen from landfill leachate poses significant challenges when implementing conventional biological techniques. These challenges arise from the leachate's higher ammonia concentration and a limited amount of biodegradable organic matter. Furthermore, the use of autotrophic and heterotrophic nitrification for leachate treatment shows to be costly, primarily due to the expenses related to aeration and carbon supply [50,51].

Effective treatment of landfill leachate is extremely important. There are several ways for treating landfill leachate, including the air stripping, electrocoagulation, chemical coagulation, and electrochemical oxidation. Their limitations include high sludge and secondary pollutant production [48].

Biological treatment offers a cost-effective, eco-friendly, and an effective solution for TN removal. Numerous biological technologies, including the moving bed biofilm reactor (MBBR), sequencing batch reactor (SBR), and membrane bioreactor (MBR), are currently being used for the treatment of wastewater applying activated sludge processes including aerobic and anaerobic microorganisms. besides to the aforementioned strategies, the discovery of Anammox has emerged as a significant advancement in the treatment of landfill leachate [49,52].

Table 3:Concentration of substances in landfill leachate by different landfill ages and climatic zones [46]

Substance's concentration (mg/L)	**Landfill age**	**Climatic zone**			
		Dry tropical zone (DTR)	Dry temperature zone (DTE)	Moist and wet tropical zone (MWT)	Wet temperature zone (WTE)
COD	Young	No data	19093.2 ± 18972.1[a]	15323.5 ± 21473.0[a]	7408.1 ± 14555.5[b]
	Intermediate	No data	8002.6 ±11312.9[b]	17994.7 ± 17194.4[a]	5097.8 ± 6039.8[b]
	Old	7973.5 ± 6973[b]	6873.3 ± 9388.5[b]	4436.7 ± 8011.2[b]	4048.2 ± 6374[b]
BOD_5	Young	No data	11055.2 ± 12258.1[a]	10839.5 ± 18043.5[a]	5306.6 ± 12519.4[b]
	Intermediate	No data	4638.3 ± 6675.4[bcd]	4884.2 ± 6542.2[bc]	934 ± 712.2[d]
	Old	2886.7 ± 3494.1[bcd]	2912.3 ± 5561.4[bcd]	1051.5 ± 2619.9[cd]	1512.4 ± 3432.1[bcd]
NH_3-N	Young	No data	1787.43 ± 1056.2[ab]	1329.3 ± 2079.0[bc]	856.0 ± 883.8[c]
	Intermediate	No data	1358.9 ± 879.3[bc]	2164.4 ± 1900.0[a]	1161.2 ± 761.1[bc]
	Old	1526.4 ± 1553.6[abc]	1303.3 ± 1565.9[bc]	1602.9 ± 1880.4[abc]	883.2 ± 925.7[c]
K^+	Non-specific	No data	921.7 ± 884.5[b]	1658.4 ± 1364.5[a]	657.7 ± 582.5[c]
Cl^-	Non-specific	6715.7± 6529.2[a]	3177.4 ± 2890.7[bc]	4248.4 ± 5466.3[b]	1724.3 ± 1885.8[c]
SO_4^{2-}	Non-specific	3566.3 ± 1293.1[a]	603.2 ± 875.5[b]	331.4 ± 446.9[b]	240.9 ± 390.7[b]

3.4 Partial nitrification and denitrification coupled with Anammox for landfill leachate treatment

The biological coupling approach, which involves the integration of Anammox with denitrification, has attracted significant attention in the past decade due to its potential for achieving high nitrogen removal efficiency [53,54]. The equations (2) and (3) depict the primary processes that take place in the Combined Partial Nitritation and Anaerobic Ammonium Oxidation (CPNA) process. The CPNA method is not dependent on the presence of an organic carbon source and results in a reduction of roughly 60% in oxygen usage [55]

$$NH_4^+ + 1.5\ O_2 + 2HCO_3^- \rightarrow NO_2^- + 3H_2O + 2CO_2 \quad (2)$$

$$NH_4^+ + 1.146\ NO_2^- + 0.071\ HCO_3^- + 0.057\ H^+ \rightarrow 0.986\ N_2 + 0.161\ NO_3^- + 0.071\ CH_{1.74}\ O_{0.31}N_{0.20} + 2.002\ H_20 \quad (3)$$

The denitrification process involves a series of four phases, wherein some enzymes play a crucial role in catalysing the transformation of nitrate into nitrogen. These enzymes are expressed in a specific sequence of functional gene expressions. Nitrite buildup is a common occurrence during the denitrification process, mostly due to the increased activity of the enzyme Nar compared to that of Nir [56].

In the treatment of Anammox effluent containing excess NO3--N, [57] implemented partial denitrification, resulting in a notable nitrogen removal efficiency (NRE) of 94.1%, demonstrating the successful achievement of partial denitrification (NO^-_3-N→NO^-_2-N).

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Using a precisely tuned mathematical model of Anammox-based procedures within Sequencing Batch Reactors treating fully developed landfill leachate, [31] investigated the effects of various operational factors on nitrogen removal efficiency. Some factors (temperature, DO,) were considered in that investigation. It accurately reproduced the changes in key physical-chemical parameters, such as total ammonia nitrogen (TAN), total nitrogen (TNN), nitrate nitrogen (NO3--N), and chemical oxygen demand (COD) concentrations. These findings provide strong evidence for the effectiveness of the process in treating leachate.

The attainment of a high nitrogen removal rate in this particular technique continues to pose a significant difficulty in its practical implementation. Several research studies have demonstrated that a reduction in temperature has a negative impact on the efficacy of nitrogen removal within the Partial Nitrification coupled with Anammox system. The ideal temperature for the growth of ammonia-oxidizing bacteria (AOB) and anaerobic ammonia-oxidizing bacteria (AnAOB) in this system has been determined to be 35℃. However, it is worth noting that the majority of these investigations have been conducted on a small scale or within laboratory settings. The actual use of PN-Anammox for wastewater treatment will inevitably be influenced by the fluctuation of environmental conditions and the composition of landfill leachate.

The first stage (1-76 days) of the research conducted by [39] examined the integrated anaerobic ammonium oxidation with partial denitrification process for enhanced nitrogen elimination from high-strength wastewater. This phase demonstrated a significant capacity for nitrogen removal, achieving an average nitrite removal efficiency above 98.0%. The principal factor contributing to the rapid reaction observed in the face of rising nitrogen influent was the increase in Anammox activity, which occurred simultaneously with a rise in temperature from 17.9 to 25.5°C. It is noteworthy to emphasize that on the 31st day, there was an insufficient nitrite elimination rate of 82.8%. The primary factor contributing to this phenomenon may be attributed to a notable decline in temperature, namely from 18.2 to 15.1°C, resulting in the inhibition of Anammox. The [58] findings indicated an ongoing reduction in the total nitrogen removal rate of the DN-PN-Anammox system as the temperature dropped from 34°C to 11.3°C. Specifically, the rate decreased from its highest point of 1.42 kg/ (m^3•day) to 0.49 kg/ (m^3•day). Below 20°C, inadequate nitrogen load in the system significantly impacts the stability of nitrogen removal, leading to significant fluctuations in high NH_4^+-N concentration. Within the temperature range of 11°C–15°C, the system effectively regulates the NLR (Nitrogen Loading Rate) to remain below 0.5 kg/ (m^3•day) (see Fig. 1) . This regulated NLR enables steady nitrogen removal, resulting in a nitrogen removal efficiency of 96%.

Engineering approaches have been designed in recent years with the goal of keeping nitrate out of the system to reduce the dosage of external C-source and a portion of the expenses associated with aeration, as nitrite is an intermediary of both the nitrification and denitrification processes. [59] showed that Anaerobic oxidation bacteria (AOB) include the genes required for denitrification processes to occur in microaerophilic environments [60]. The findings of [61] investigated that only approximately 1.7% of the nitrogen remnants were found in the effluent, resulting in a high nitrogen removal efficiency (NRE) of 98.3%. Consequently, the three-stage SAD process presented offered a viable technical option for achieving energy-positive operations in wastewater treatment plants. Hence, when compared to the NO_3^--N wastewater and domestic wastewater, using the technique of partial denitrification along with Anammox presents a viable approach for achieving nitrogen removal. This process offers significant benefits, including minimal carbon requirements, absence of aeration consumption, reduced sludge generation, and reduced emission of greenhouse gases (refer to Fig. 2) [61].

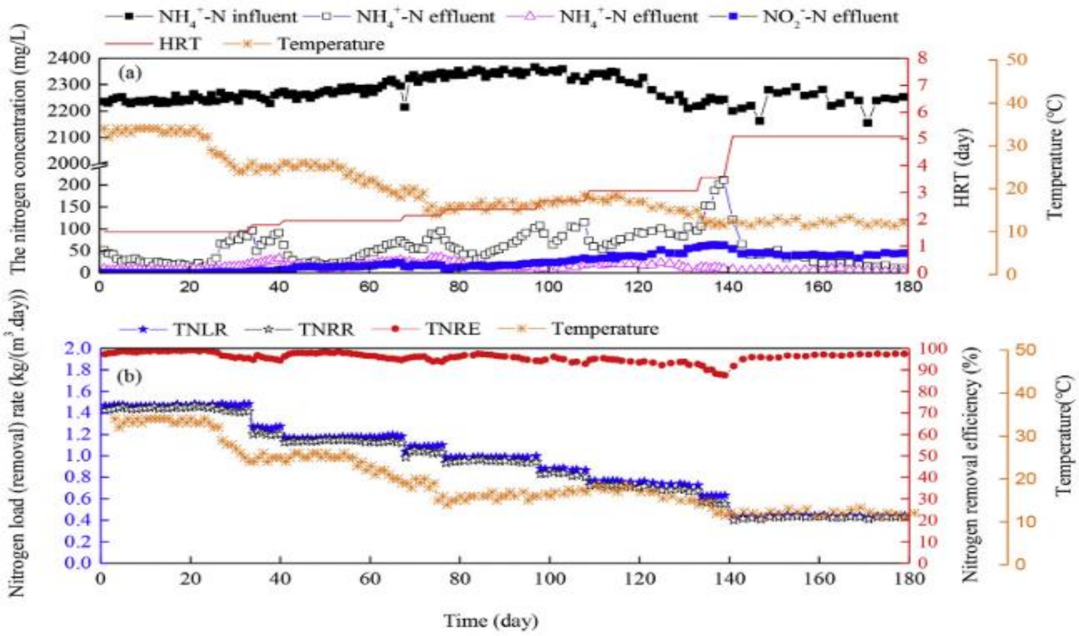

Figure 1: The effect of temperature change on the nitrogen removal of DN-PN-Anammox system [58]

For treating mature landfill leachate over a 180-day period, [62] created an inventive two-stage PN/A-PDN/A (partial nitrification and Anammox and partial denitrification and Anammox) system using numerous NO_2^--N supplement pathways. When the effluent quality included concentrations of 3.2 mg/L NH4+-N, 1.6 mg/L NO_2^--N, and 3.1 mg/L NO_3^--N, an impressive nitrogen removal efficiency of 98.8% was attained. Anammox has been identified to be the primary pathway for nitrogen elimination, making a significant contribution of up to 87.9%. Furthermore, in circumstances characterized by a 1.5-fold increase in incoming substrates and an 8.0-fold increase in aeration overload, a high level of stability in the Anammox process was successfully attained. In contrast to the typical nitrification-denitrification process, the use of PN/A-PDN/A resulted in a significant reduction of 95.1% in the organic carbon demand, a notable drop of 61.5% in the energy consumption associated with aeration, and a substantial decline of 77.6% in the production of biomass.

While nitrite-oxidizing bacteria are inhibited, leading to the accumulation of nitrite, ammonia-oxidizing bacteria (AOB) exhibit increased abundance and activity throughout the partial nitrification (PN) process. Combining PN and Anammox might result in fully autotrophic nitrogen removal [19,63].

Partial nitrification combined with Anammox has too some limitations. [38] findings demonstrated that the PNA nitrogen removal activity might be inhibited by the abrupt adding of even a tiny amount of seawater to sewage with a relatively low leading to salinity of roughly 6.5‰.

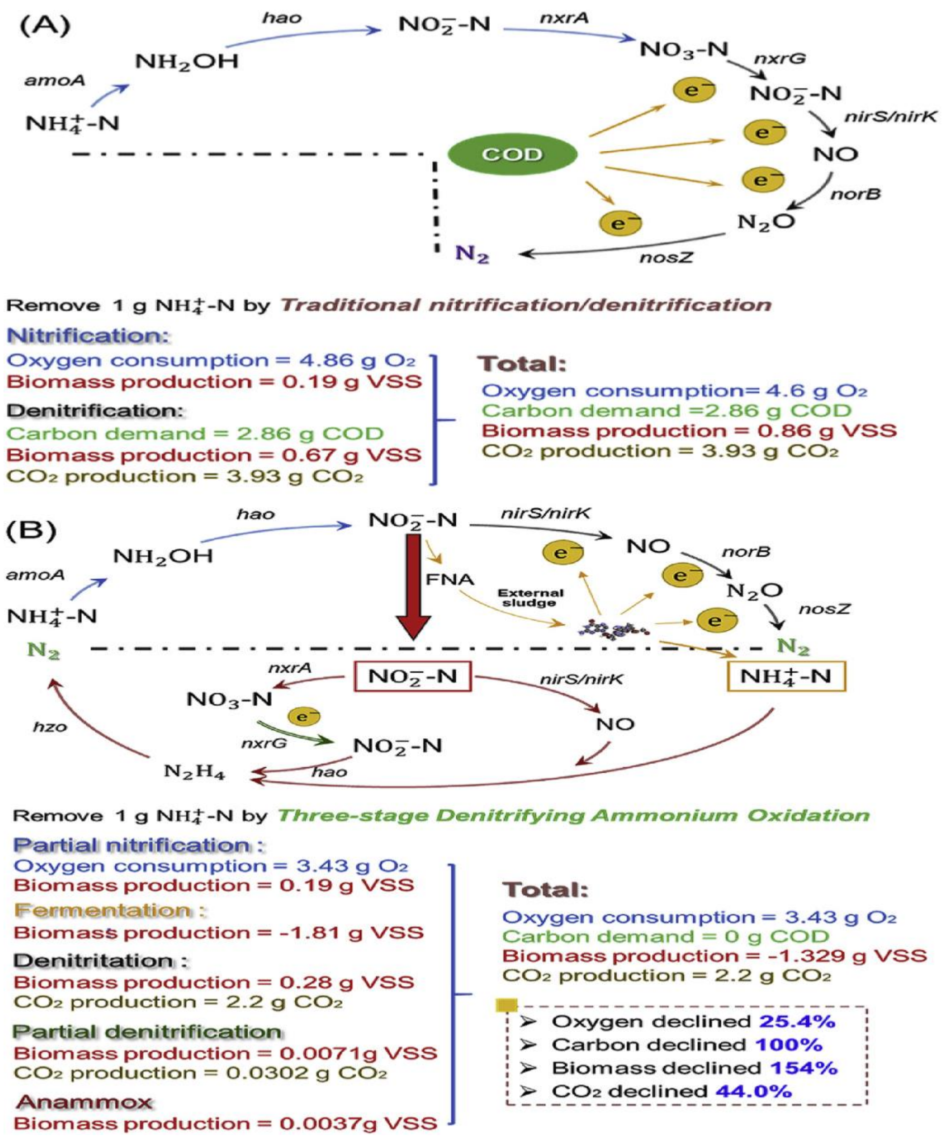

Figure 2:Comparison of Removing 1 g NH4+-N by traditional nitrification/denitrification (A) and Three-stage Simultaneous Ammonium oxidation Denitrifying process (B) in terms of biomass production, carbon demand, oxygen consumption and CO_2 production [61].

As a breakthrough in this field, the PN Anammox coupled PD method has been adopted extensively in the treatment of landfill leachate. There are many other ways to combine the aforementioned technologies; they include one-stage PNA + PDA, two-stage PNA-PDA, three-stage PN-A-PDA, and two-stage PN-PDA procedures. The combination processes may be implemented in batch systems that run continuously or in a sequence, and they are not limited by the kind of reactors used.

3.5 Other techniques for landfill leachate treatment

For eliminating high concentrations of Chemical Oxygen Demand and ammonia from composting leachate, the efficacy of a novel hybrid airlift bioreactor (HALBR) operated with biofilm coated carriers and activated sludge in continuous mode was evaluated in [45] research. They successfully treated composting leachate rich in nitrogen. The total COD and TN removal efficiencies were 82–96% and 49.83–85.3%, respectively. Anaerobic conditions at HALBR's bottom helped hydrolyze and acidify organic molecules to improve COD removal efficiency. Specific geometry and associated growing biomass were needed for the simultaneous nitrification-denitrification process, which removed nitrogen solely. The empirical results indicate that the introduction of an anaerobic zone in the lower section of an airlift bioreactor can enhance the treatment of fresh composting leachate containing slowly biodegradable chemical oxygen demand (COD). The enhancement of anaerobic hydraulic retention time (HRT) resulted in a notable improvement in the breakdown of feed, hence highlighting the significance of solubilization in the removal of organic waste.

[46] study offered significant data on global landfill leachate, which might help in reducing pollution and achieving sustainable municipal solid waste management goals. The authors developed an extensive worldwide database of physicochemical characteristics pertaining to landfill leachate, drawing from scientific literature. This database has a total of 1251 data points derived from 236 distinct provinces or cities across 51 different countries. Different methods aggregated landfill leachate contaminant concentrations depending on countries, climate, and landfill age categories [64].

In [22] research, the phytotoxicity of leachate was examined utilizing *Lemna minor* (duckweeds), an easily cultivated, petite, rapidly proliferating plant that has a floating nature. *Lemna minor* demonstrates a high efficiency of performance in the removal of ammonia nitrogen from wastewater, while also exhibiting ability to capture heavy metals. This characteristic renders it a valuable indicator in the assessment of landfill leachate toxicity. The study also examined the genotoxicity of wastewater using *Allium cepa* (onion) using PCR-RAPD method and found that untreated municipal landfill leachate in southern Poland and SBR reactor effluent exhibit phytotoxicity for *Lemna minor* due to high concentrations of organic compounds, heavy metals, and a unionized form of ammonia (NH_3). The study suggested that ANAMMOX might be a valuable tool for reducing the phytotoxicity of landfill leachate.

The efficiency of the treatment in eliminating the genotoxic chemicals contributing to the effluent's mutagenic potential was found to be insufficient in the *Allium cepa* test. Even after leachate treatment, the genotoxic potential was detected, which was not connected with heavy metal impacts such free radical production or chemical compounds and suggested that other leachate compounds not examined in the research might induce genotoxicity.

4. Future perspectives

Most of research conducted on Anammox has identified many common problems, including the long start-up time, limited quantity of Anammox bacteria, and a slow growth rate. These factors all contribute to a reduction in the overall efficiency of the reaction. The achievement of a high nitrogen removal rate remains a significant difficulty in the actual implementation of this method of removal.

Long start-up times and a low rate of proliferation are some challenges of the Anammox process. The growing atmosphere is highly vulnerable for the Anammox bacteria, which makes it challenging to implement the technique extensively [65].

[38] findings demonstrated that the PNA nitrogen removal activity might be inhibited by the abrupt adding of even a tiny amount of seawater to sewage with a relatively low leading to salinity of roughly 6.5‰. The challenges associated with implementing partial nitritation and Anammox processes (PN/A) for nitrogen removal in urban wastewater treatment plants have been identified and include the reduced stability of PN/A units and the increased presence of nitrite-oxidizing bacteria in the mainstream.

Limited study has been conducted on the treatment of leachate. There are several ways for treating landfill leachate, including the air stripping, electrocoagulation, chemical coagulation, and electrochemical oxidation. Their limitations include high sludge and secondary pollutant production. The chemical composition of the landfill leachate has been mentioned as an issue for the Anammox bacteria react differently. Research is encouraged in this way as well. Reducing the mountains of solid wastes found in the environment, especially in Africa must be a warning point to do, not only small-scale applications of innovative and sustainable systems as most of the research made about Anammox but also to promote these technologies at the big scale.

By adopting suitable technology for landfill application, it is possible to transform landfills in Africa into a viable energy source for home and commercial purposes, therefore mitigating their current adverse environmental and health impacts [66].

5. Conclusion

Higher waste generation from industrialization and urbanization has caused serious ecological damage if not properly treated. In addition, treatment systems that recover bio-products, nutrients, and energy are prioritized. The Anammox combined with other systems (Partial nitrification for instance) has been found to reduce excess nitrate residual in effluent, achieving more than 97% nitrogen removal efficiency. Treating landfill leachate resulted in an excellent NH_4^+-N removal efficiency. However, most of the research conducted reported some limitations of the technology on a small scale such as the low start-up time affecting the growth of bacteria in the reactors and the instability of the system when pH and temperature decrease. The Anammox method has been widely investigated nitrogen removal from landfill leachate, due to its remarkable effectiveness. The method in question exhibits reduced operation costs and generates a lesser amount of waste sludge in comparison to alternative approaches, attributable to its lower waste sludge output and cost-effectiveness.

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Conflict of interest

The authors declare no conflict of interest.

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