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Floating treatment wetland enhanced with nanobubbles aeration system for nitrogen removal as a sustainable domestic wastewater treatment

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ABSTRACT

Water pollution from domestic wastewater remains a significant environmental concern, necessitating efficient and sustainable treatment solutions. This study evaluates the performance of Floating Treatment Wetlands (FTW) enhanced with nanobubble aeration (FTW-MB) for improving water quality through the removal of ammonia, nitrate, total nitrogen (TN), and total suspended solids (TSS). This research is carried out in a batch reactor and observed for 13 days. In floating treatment systems, floating mats were planted with 11 clumps of *Vetiveria zizanoides.* Three treatment systems – nanobubble aeration (NB), FTW, and FTW-NB – were tested to assess their pollutant removal efficiencies. The results showed that NB aeration significantly increased dissolved oxygen (DO) levels and enhanced ammonia oxidation to nitrate. Ammonium removal was nearly complete in both the NB and FTW-NB systems (100%) in 5 and 6 days, while FTW achieved 97.86% ammonium removal in 13 days, indicating that NB aeration accelerates nitrification by providing a higher oxygen supply. TSS removal was most effective in the NB system (95.35%), suggesting that NB aeration improved sedimentation and particle flotation. FTW-NB provided a balanced approach and integrated plant-based treatment with increased oxygenation. These findings demonstrate that FTW-NB is the most effective system for nitrogen reduction in wastewater treatment, while NB aeration optimizes oxygen availability and enhances microbial degradation. To increase the effectiveness of treatment for the plant pollutants, future studies should improve the positioning of NB aeration in FTW systems.

Keywords: floating treatment wetland, nanobubble aeration, wastewater treatment, nutrient removal, water quality improvement, integrated treatment system.

INTRODUCTION

Water scarcity, both in terms of quality and quantity, is a significant concern when evaluating wastewater treatment options that must be comparable to traditional methods in terms of efficiency and operational costs. The development of green technologies is one promising alternative to remedy environmental pollution problems. This green technology has the potential to reduce ecological impact through energy efficiency, safe recycling, and the utilization of renewable resources (Laffta and Al-rawi, 2017).

A floating treatment wetland (FTW) is an ecosystem engineering technology that uses natural processes to improve water quality. These systems consist of floating structures where aquatic plants thrive. These plants' roots develop in the water column, while their stems and leaves emerge above it. Microorganisms in the root system work with plants to absorb nitrogen, phosphate, carbon, and other pollutants via adsorption, absorption, and microbial degradation pathways (Vymazal, 2010; Chance et al., 2019; Oliveira et al., 2021). The root system serves as a habitat for microorganisms like bacteria and fungi, which work together to break down organic substances. The FTW improves ecosystem services by creating new habitat for aquatic biota such as periphyton, small fish, and crustaceans, promotes biodiversity, and provides aesthetic value. Furthermore, the root system helps to provide the dissolved oxygen required by aerobic microbes to carry out pollutant breakdown and filtration activities (Dotro et. al., 2019).

Dissolved oxygen level in the water column can be increased by adding an aeration system to the FTW. Nano-sized aeration systems have been developed and implemented in wastewater treatment and have become one of the most promising green technologies. Nanobubbles can enhance dissolved oxygen levels in the water column and provide aerobic conditions, which are critical for nutrient uptake and pollutant breakdown by microbial communities and plants.

Nanobubble (NB) aeration is useful in optimizing biofilters that reduce ammonia through the mass transfer process. Biofilter effectiveness is greatly impacted by oksigen availability (Havlí˘cek et al., 2021). NB aeration produces reactive oksigen species that may accelerate the oxidation process of organic pollutants and promote the growth of biofilm in the rhizosphere. Due to these factors, ammonia degradation through nitrification will be increased (Wu et al., 2021; Reveto et al., 2019; Oktaviyani et al., 2024). Because nanobubbles have a high surface area-to-volume ratio, they significantly increase the efficiency of oxygen transmission. NB oxygenation enhances the growth of aerobic bacteria, facilitates the removal of suspended particles, and improves the overall efficacy of wastewater treatment.

For the treatment of domestic wastewater, FTWs and NB aeration offer a number of benefits, including low energy needs, less chemical use, and compatibility with current treatment equipment. From small-scale home applications to massive municipal wastewater treatment plants, these technologies can be scaled up or down to improve environmental health and water quality. However, little is known about how FTW and NB aeration might work together to reduce contaminants in greywater.

A promising development in the treatment of domestic wastewater is the combination of FTWs with NB aeration. In addition to effectively removing pollutants, these technologies support the preservation of aquatic ecosystems and the conservation of natural resources. They have the potential to be essential parts of worldwide sustainable water management plans with more study and wider use. The objective of this research is to examine the potential of *Vetiveria zizanoides*, often known as vetiver grass, as a floating plant in FTW that is enhanced with NB aeration, both individually and in combination, to eliminate contaminants from domestic wastewater.

MATERIALS AND METHODS

Nanobubbles pumps

The NB aerator pump was placed in the middle of the container to ensure an even distribution of oxygen throughout the wastewater. The pump operates at a power of 20 watts, utilizing a swirl type, and is equipped with a nozzle to produce oxygen nanobubbles, as shown in Figure 1 and Table 1.

The aeration pump test conducted on three pumps reveals significant bubble size distribution, concentration, and uniformity variations. Pump 2 demonstrates the most stable and uniform nanobubble formation, as indicated by its lowest polydispersity index (0.584) and the dominant peak at 517.2 nm with 82% intensity, ensuring efficient oxygen transfer and stability. Additionally, Pump 2 lacks larger bubble formations, with a maximum undersize value of 1110 nm, suggesting minimal aggregation and higher system efficiency. In contrast, Pump 1 generates the highest concentration of bubbles, as reflected in its highest derived kcps (1228.7); however, it also exhibits greater polydispersity (0.689) and an additional peak at 5341 nm, indicating the presence of larger bubble clusters, which could reduce overall aeration efficiency. Pump 3, with a Z-average of 530.2 nm, produces slightly larger bubbles compared to the others but remains relatively stable, lacking extreme size outliers like Pump 1.

The undersized results further highlight these differences, where pump 1 produces the largest bubbles at the 100% percentile (6440 nm), while pump 2 maintains the smallest range (1110 nm), confirming its consistency in nanobubble production. The median bubble size in pump 2 is the smallest at 456 nm, reinforcing its efficiency in applications requiring fine and uniform bubble dispersion. Meanwhile, pump 3 remains a balanced option, with moderate bubble sizes and relatively

Table 1. Cumulative and distribution results of NB aeration tested on 3 pumps

Cumulative results		Distribution results					Undersize results	
Z-avg (nm)	468.8		Size (d.nm)	% Int	T	%Pd	Di (%)	Size (d.nm)
Pd index	0.689	Peak 1	640.0	76.4	204.4	31.9	10	125
Pd (nm)	389.1	Peak 2	124.9	18.4	27.92	22.3	50	565
%Pd	83.0	Peak 3	5341	5.1	360.3	6.7	90	1020
Derived kcps	1228.7						100	6440
Cumulative results		Distribution results					Undersize results	
Z-avg (nm)	480.8		Size (d.nm)	% Int	T	%Pd	Di (%)	Size (d.nm)
Pd index	0.584	Peak 1	517.2	82.0	155.6	30.1	10	117
Pd (nm)	367.6	Peak 2	116.4	18.0	28.02	24.1	50	456
%Pd	76.5	Peak 3	0.0	0.0	0.0	0	90	720
Derived kcps	1073.6						100	1110
Cumulative results		Distribution results					Undersize results	
Z-avg (nm)	530.2		Size (d.nm)	% Int	T	%Pd	Di (%)	Size (d.nm)
Pd index	0.621	Peak 1	593.4	80.6	153.0	25.8	10	124
Pd (nm)	417.8	Peak 2	125.2	19.4	25.70	20.5	50	527
%Pd	78.8	Peak 3	0.0	0.0	0.0	0	90	798
Derived kcps	1094.2						100	1280

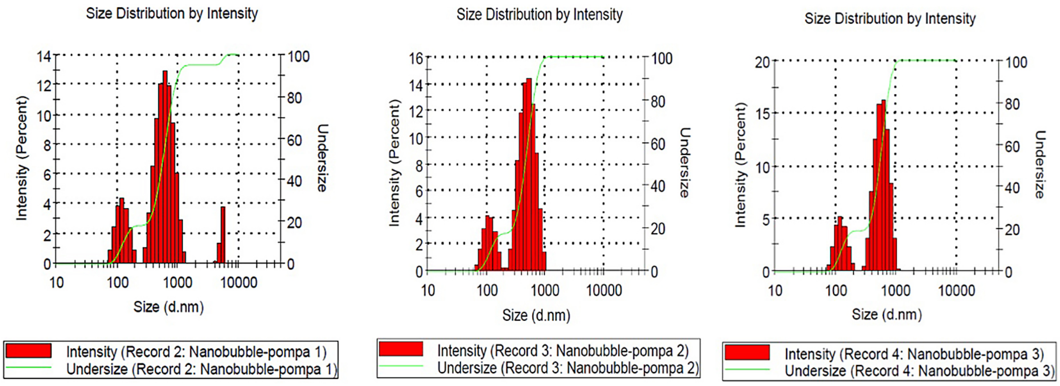

Figure 1. Size distribution of aeration of the nanobubble pump

low polydispersity (0.621), making it suitable for applications where slightly larger bubbles may be beneficial. Overall, pump 2 is the best candidate for generating uniform and efficient NB, ideal for applications in wastewater treatment, aeration, or chemical processes, whereas pump 1 may be more suitable for cases where a higher concentration of bubbles is required, albeit with additional control measures to minimize large bubble formation.

Based on the table and graph above, the average bubble size (Z-average) for the three pumps ranges between approximately 468.8 nm and 530.2 nm, with peak distributions predominantly below 1 µm. ISO 20480-1:2017 defines ultrafine bubbles (nanobubbles) are those with a volume equivalent radius of below 1 µm. The data from all three pumps indicate that the majority of the bubbles fall within this NB size range, confirming that the aeration systems tested produce NB rather than microbubbles. Therefore, all three pumps can be classified as NB generators based on their measured size distributions.

The average zeta potential of -17.7 mV, which indicated moderate particle stability, was found in the zeta potential analysis of the NB produced by the NB pump (Table 2; Figure 2). The zeta potential distribution revealed two distinct peaks, one at -10.2 mV (68.9%) and another at -35.4 mV (31.1%), suggesting two populations of bubbles with different levels of stability and size. The measured conductivity of the solution was low (0.0197 mS/cm), ideal for enhancing nanobubble

Table 2. Zeta potential of nanobubble pumps

Parametert	Mean (mV)	Area (%)	Standard deviation (mV)
Zeta potential: -17.7	Peak 1: -10.2	68.9	8.35
Zeta deviation: 14.5	Peak 2: -35.4	31.1	7.90
Conductivity (mS/cm): 0.0197	Peak 3: 0.00	0.0	0.0

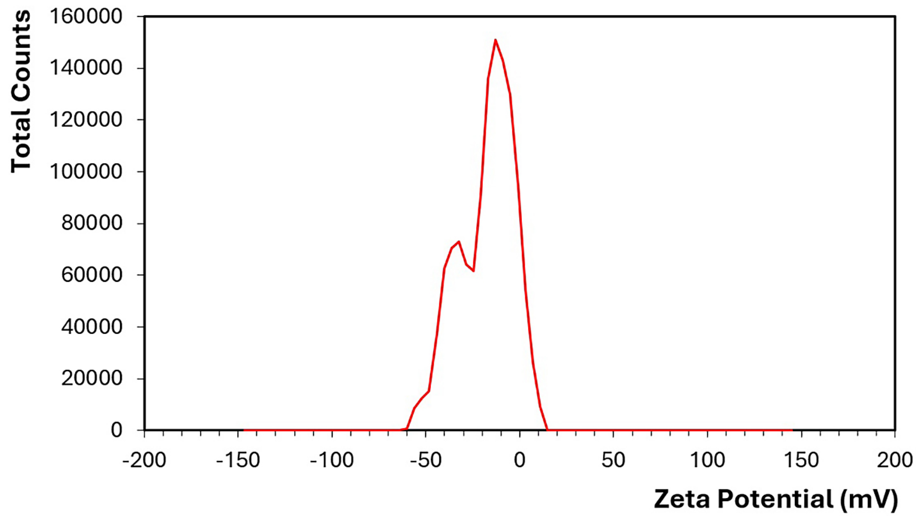

Figure 2. Zeta potential distribution of nanobubble pumps

stability due to minimal ionic interference. Measurements were conducted at 25°C, with a fluid viscosity of 0.8872 mPa.s and a refractive index (RI) of 1.330, consistent with pure water. Overall, these results indicate that the nanobubble pump effectively produces bubbles with acceptable stability for various applications.

The negative value zeta potential indicates stable nanobubbles with negatively charged surfaces that can attract cations and allow continuous oxygen diffusion in the water, ensuring oxygen levels are high enough for the ammonia oxidation process. The zeta potential of air micro-nano bubbles is between -20 mV and -17 mV, while the zeta potential of oxygen micro-nano bubbles is between -45 mV and -34 mV; this value represents the interfacial potential of the micro-nano bubble (Liu & Tang, 2019).

Schematic design of treatment

The research was conducted on a pilot-scale setup using nine container boxes, each serving as a reactor with a volume of 70 liters (dimensions: 60 × 42.5 × 38 cm). Each container was filled with 50 liters of domestic wastewater in a batch system (Figure 3). The experiment consisted of three treatment variations: (a) continuous NB aeration (NB), (b) floating treatment wetland (FTW), and (c) a combination of FTW and NB aeration (FTW-NB). Each treatment was replicated three times and observed over 13 days. In FTW (b) and FTW-NB (c) systems, floating mats were planted with 11 clumps of *Vetiveria zizanoides*, which had undergone a two-week acclimatization period before the experiment.

Domestic wastewater

The domestic wastewater used in this study was sourced from laundry and hand-washing activities and was characterized based on pH, COD, total ammonia nitrogen (TAN), nitrate, total nitrogen, phosphate, total phosphorus, dissolved oxygen (DO), and total suspended solids (TSS). Additionally, physicochemical qualities such as pH, DO, temperature, and total dissolved solids (TDS) were evaluated daily using a water quality checker (Horiba U-50). The experiments were conducted in a greenhouse at the Research Center for Limnology and Water Resources – BRIN, while water sample analyses were performed in the Hydrochemistry Laboratory, following the APHA-AWWA Standard Methods (2017). Ammonia, nitrate, and total nitrogen were determined and analyzed via Spectrophotometry. TSS were analysed using the

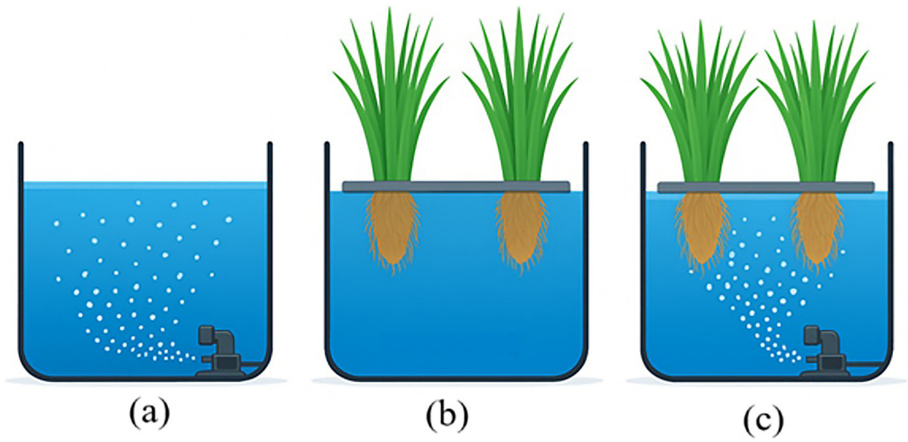

Figure 3. Schematic design system treatment of (a) NB, (b) FTW, and (c) FTW-NB

gravimetric method. Parameter of nitrogen as ammonia, nitrate, total nitrogen, and TSS, was evaluated daily, and the results were reported as mean values with standard deviations.

Analysis of data

The percent of contaminants removed for each type of treatment system unit was determined using the equation of Wang et al. (2010):

$$ER = \frac{C_{t=0} - C_t}{C_{inlet}} \times 100\% \quad (1)$$

where: $C_{t=0}$ is the pollutant concentration at the initial time (t=0), C_t is the pollutant level at a certain time t, and ER represents the removal efficiency (%).

The statistical analyses focused on the contaminant concentrations of key water quality parameters, including ammonia, nitrate, total nitrogen, TSS, DO, and pH across different treatment systems. Two-way repeated measurements ANOVA was utilized to assess the impact of treatment type (Factor A) and contact time (Factor B) on each water quality parameter. Significant differences were detected ($p < 0.05$). The level of difference between treatments was further tested using the Duncan test. The statistical calculations were done with SPSS version 21 (IBM Statistics, USA).

RESULTS AND DISCUSSION

Characterization of domestic wastewater

Visually, domestic wastewater emits an unpleasant odor, appears blackish and turbid, and contains high levels of suspended solids (Figure 4). Table 3 shows the initial properties of the wastewater. The DO concentration in the wastewater is extremely low, approaching anoxic

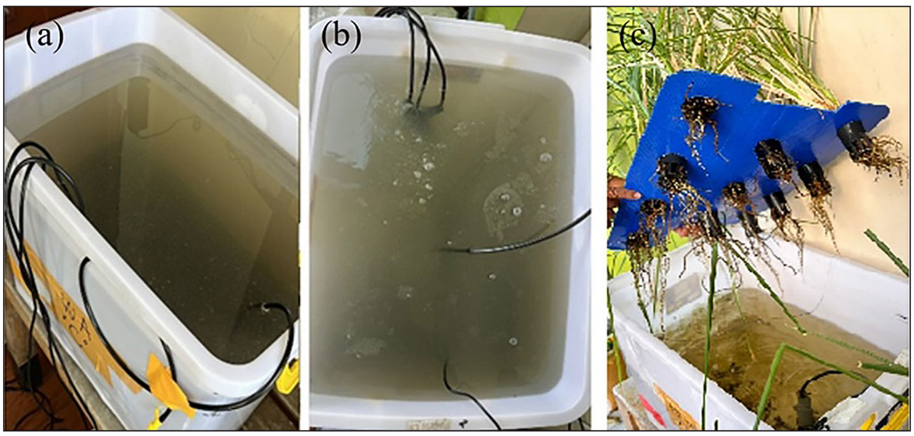

Figure 4. Domestic wastewater appearance (a) before, (b) NB aeration at t = 0, and sedimentation in the FTW tank

Table 3. The characteristics of domestic wastewater

Parameter	Unit	Concentration
pH		7.57
DO	mg/L	0.90
TDS	mg/L	475.375
COD	mg/L	206.667
TN	mg/L	23.461
TAN	mg/L	20.668
Nitrate	mg/L	0.169
TP	mg/L	1.240
Phosphate	mg/L	0.742
TSS	mg/L	24.0

conditions, and is accompanied by high COD, ammonia, and TSS concentrations. The low DO level (0.9 mg/L) indicates that nitrate reduction occurs anaerobically.

According to Al-Ajalin et al. (2020), greywater COD concentrations typically reach 234 mg/L, with ammonia and phosphate levels of 12 mg/L and 5 mg/L, respectively. However, the domestic wastewater used in this study exhibits higher concentrations of ammonia and total nitrogen but lower phosphate and total phosphorus levels. Greywater serves as the primary source of organic compounds, while kitchen and laundry activities contribute to nitrogen (N) and phosphorus (P) inputs (Oteng-Peprah et al., 2018; Al-Ajalin et al., 2020; Widyarani et al., 2022). The free ammonia concentration increases as DO levels decrease, influenced by pH and temperature fluctuations (Effendi, 2018). As reported by Emerson et al. (1975), higher pH and temperature levels promote increased ammonia concentrations while reducing ammonium ion levels.

The plant growth

Vetiver in both the FTW and FTW-NB exhibited increased growth in height, with an average growth rate of 20.267% and 24.155%, respectively. The higher growth rate observed in the FTW-NB suggests that NB aeration enhances plant development compared to the FTW without aeration (Figure 5). The beneficial effects of NB aeration on vetiver growth became evident after 14 days of observation. The FTW-NB consistently outperforms the FTW in promoting plant height, demonstrating the positive influence of NB aeration. The difference in plant height is most pronounced at day 14, suggesting that prolonged exposure to NB aeration further amplifies the benefits.

By raising DO levels, NB aeration enhances vetiver's nutrient absorption efficiency while promoting microbial activity and root health (Arablousabet and Povilaitis, 2024). Furthermore, it promotes the dispersion and breakdown of nutrients, increasing the bioavailability of phosphorus and nitrogen, two elements essential for plant growth. More effective mineralization and nutrient absorption are encouraged by the negatively charged surface of NB, which draws in positively charged nutrient ions (Wang et al., 2021).

Performance of the systems

DO concentration and pH trends over 13 days are shown in Figure 6a. DO concentration in the NB Aeration system is effective at improving oxygen dissolution and consistently maintains the highest DO levels (7.20–8.12 mg/L) and increases for 24 hours. On the other hand, FTW exhibits a limited natural aeration capacity, beginning with a very low DO (~1 mg/L) and increasing gradually to ~3.99 mg/L. The FTW-NB shows moderate DO levels (6.63–7.90 mg/L), which are lower than the NB Aeration system but higher than FTW. This suggests that NB aeration enhances microbial and plant activity by supplementing the wetland's oxygenation process.

In comparison to the other two systems, NB aeration can maintain the greatest pH, which is between approximately 8.2 and 8.6, as seen in Figure 6b. FTW's root system produces CO_2 from microbial respiration, which puts it in the lowest pH range (7.4–7.6). By maintaining a pH range of 7.8 to 8.2, FTW-NB demonstrates a rise, which indicates how DO concentration and pH stability

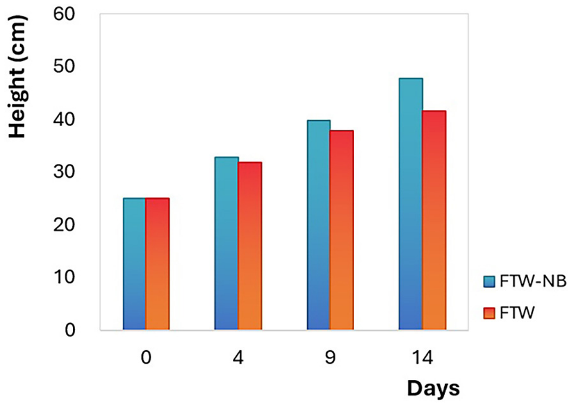

Figure 5. The plant growth in the system with and without nanobubble aeration

can be enhanced by NB aeration. The outcome is improved conditions for wastewater treatment (Arablousabet and Povilaitis, 2024; Gupta et al., 2024). By fusing the ecological benefits of floating wetlands with the efficiency of NB aeration, FTW-NB provides better oxygenation and pH regulation than the FTW system.

When gases like CO_2 are dissolved in the water column, carbonic acid is produced, which can lower pH levels. Depending on the initial water composition, oxygen NB might have a neutral or slightly alkaline effect. NB oxygen helps maintain pH stability by ensuring uniform gas dissolution across the water column and minimizing localized pH variations. The solubility of DO is strongly influenced by temperature; at higher temperatures, oxygen becomes less soluble in water. Throughout the observation period, the water temperature (26.68–31.34 °C) remained relatively stable, which lessened its impact on oxygen solubility. However, higher temperatures can shorten the lifetime of NB due to changes in gas solubility and increased kinetic energy. Nevertheless, NB enhances overall gas dissolution in water, even though its efficacy is still temperature-dependent.

Through their root systems, aquatic plants in the FTW release oxygen into the water through photosynthetic activity, raising DO levels, which are essential for microbial activity in nutrient removal. By directly affecting the redox conditions in the water column, the DO concentration promotes the nitrification process, which turns ammonia into nitrate. Furthermore, increased DO levels promote microbial activity, which improves the breakdown of nutrients and organic compounds (Colares et al., 2020).

TDS are comprised of dissolved materials like salts, minerals, and organic materials, whereas TSS are comprised of solids suspended in water and derived from soil, mud, and organic matter. According to Boyd (2000) and Wetzel (2001), both measurements are important indicators of water quality. All treatment systems exhibit a steady rise in TDS over time, as seen in Figure 7, which suggests that organic matter and mineral dissolution are continuing. The highest TDS accumulation is seen in the FTW-NB, indicating that the combination of NB aeration and FTW improves microbial activity and nutrient release from the breakdown of organic matter.

In contrast, the FTW system maintains a consistently high TDS level but does not increase as sharply as FTW-NB, implying that while plant roots contribute to nutrient cycling, the absence of NB aeration may limit additional dissolution. NB Aeration system starts with the lowest TDS and increases at a more controlled rate, indicating a more gradual breakdown of dissolved substances

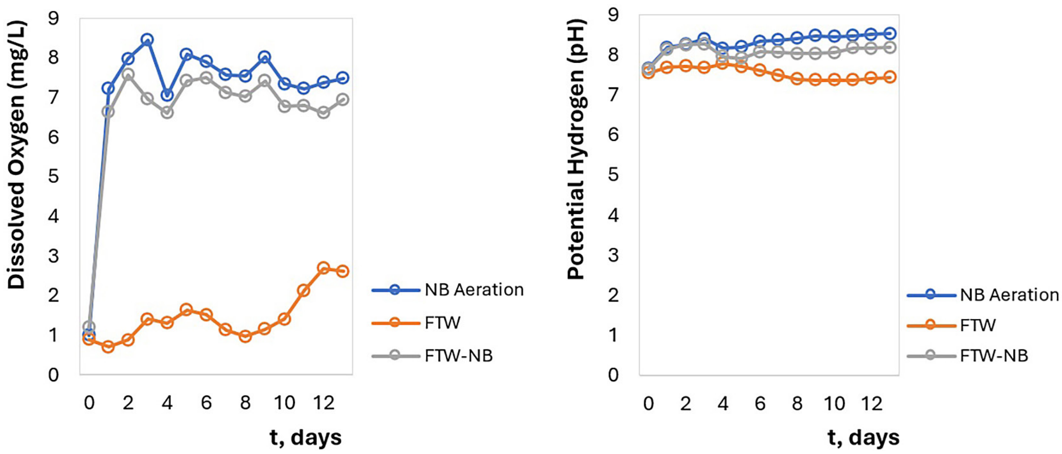

Figure 6. The concentration of DO (a) and pH (b)

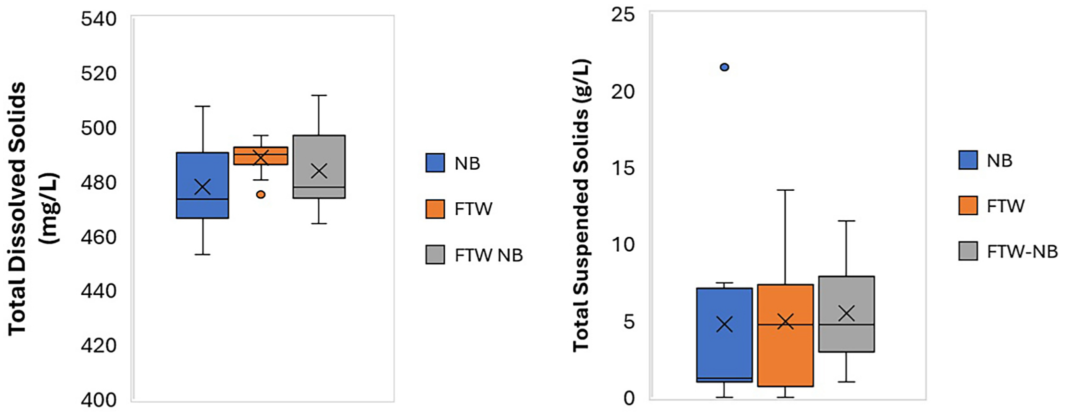

Figure 7. Concentration of TDS and TSS

without the influence of wetland-root interactions. The overall rise in TDS across all treatments suggests that microbial decomposition and biochemical processes continue throughout the observation period, releasing dissolved organic and inorganic compounds into the water column.

The TSS trend in Figure 7 indicates a gradual decline across all treatment systems, reflecting the sedimentation and decomposition of particulate matter over time. The NB Aeration initially has the highest TSS (~22 g/L) but shows a rapid decrease, reaching nearly 0 g/L by day 9, suggesting that NB aeration enhances the breakdown and settling of suspended particles. The FTW also experiences a steady decline in TSS, stabilizing at lower levels, indicating that the plant roots contribute to sedimentation but with less turbulence compared to aeration-based systems. The FTW-NB exhibits fluctuations before eventually decreasing, likely due to the temporary resuspension of particles caused by root activity and biofilm detachment, which then settle as microbial processes progress. The most stable reduction in TSS is generally achieved by the NB aeration system, whereas FTW and FTW-NB depend on microbial and biological interactions, which cause periodic fluctuations before particulate removal is achieved.

It has been demonstrated that NB aeration improves TSS removal by making it easier for suspended particles to separate and float. The efficiency of separation is improved by the nanobubbles' increased contact with particles due to their high surface area-to-volume ratio. Because of its high specific surface area and strong zeta potential, NB improves adhesion efficiency and lengthens the time that the bubble and the suspended material remain in contact. Furthermore, reactive oxygen species (ROS) generated by oxygen NB, such as the highly oxidizing radical hydroxyl, aid in the breakdown of both organic and inorganic materials (Liu and Tang, 2019). By dissolving pollutants, the maintenance particles in suspension decrease organic suspended solids, and converting dissolved solids into particulate forms, this oxidative process can ultimately reduce TSS levels (Chan et al., 2020). Additionally, NB aeration enhances oxygenation by encouraging aerobic microbial activity in the decomposition of dissolved organic matter (DOM). Through the conversion of DOM into carbon dioxide and water, this biological activity effectively lowers TDS levels. NB promotes the development of biofilms on media surfaces and vetiver roots, which capture and break down dissolved particles, thereby improving TDS efficacy.

TSS is mostly decreased in the FTW through the settling process, which is aided by gravity and less water movement in batch systems. To capture suspended particles and reduce TSS levels, the filtration mechanism of the vetiver root system is crucial (Dorafshan et al., 2023). Plant roots and the biofilms that develop on their surfaces help to capture nutrient-rich particles, which lowers nutrient concentrations in the water. The sedimentation process further reduces nutrient concentrations by allowing nutrient-bound particles to fall to the bottom (Colares et al., 2020). However, there is a chance that plant measurements and water sampling will temporarily resuspend settled solids back into the water column, which would alter TSS levels in the FTW and FTW-NB systems. The studies show that NB enhances the DO concentration, which accelerates the settling of suspended particles and improves the removal efficiency of TSS.

The higher oxygen presence facilitates the oxidation of ammonia to nitrate by releasing OH^- ions and raising pH levels. Ammonium is converted into nitrite and nitrate during the nitrification process, which is improved by NB aeration. Microbial nitrification is accelerated by nanobubbles' increased surface area and high reactivity, which give bacteria more places to act. Furthermore, oxygen nanobubbles' oxidative qualities allow them to directly oxidize ammonium, turning it into nitrogen gas or other nitrogenous compounds and lowering ammonium concentrations in the process. Since nitrification is both pH-sensitive and temperature-dependent, the relationship between pH, temperature, and ammonium levels is extremely complex. NB stabilize microbial activity and increase overall nitrification efficiency by supplying a steady oxygen supply, which aids in the regulation of these processes.

Figure 8 illustrates the decline in total ammonia nitrogen (TAN) concentrations across the three treatment systems over 13 days. All systems demonstrate a gradual reduction in TAN, indicating ongoing nitrification and ammonia removal processes. However, NB Aeration and FTW-NB exhibit the fastest ammonia reduction, with TAN levels approaching zero within the first 5–6 days, suggesting that NB aeration enhances oxidation and microbial nitrification by increasing dissolved oxygen availability. In contrast, the FTW system shows a slower TAN removal rate, reaching complete removal only after day 10, likely due to limited oxygen diffusion, which slows the conversion of ammonia to nitrate. These findings suggest that NB aeration significantly accelerates the ammonia removal process, particularly when combined with FTW.

Figure 9 shows the corresponding increase in nitrate (NO_3^-) concentrations, confirming that ammonia oxidation via nitrification is occurring. NB Aeration leads to the highest nitrate accumulation (~12 mg/L by day 13), indicating efficient ammonia conversion, as oxygen-rich conditions support microbial activity. FTW-NB shows moderate nitrate production, reflecting a balance between microbial nitrification and plant uptake of nitrogen. The lowest nitrate levels are maintained by the FTW system, indicating that some of the eliminated TAN is absorbed by plants rather than completely transformed into nitrate. The importance of oxygen availability in enhancing nitrification efficiency is further highlighted by the delayed accumulation of nitrate in FTW.

The NB aeration system exhibits the best TAN removal and nitrate production, demonstrating that oxygen-rich conditions support microbial nitrification processes. By employing both microbial and plant-based nitrogen removal mechanisms, the FTW-NB provides an effective balance, making it a promising wastewater treatment solution. However, because FTW relies more on plant absorption and natural microbial activity, ammonia elimination is slower, and nitrate accumulation is lower. These results suggest that by accelerating ammonia oxidation while maintaining plant-based nitrogen uptake, FTW and NB aeration combine to optimize nitrogen transformation. Because of this, it's a particularly successful method for wastewater treatment applications.

Colares et al. (2020) state that vetiver roots absorb nitrogen as NO_3^- and NH_4^+. In this mechanism, vetiver mostly employs ammonium as a nutrient for growth since it is less energy-intensive to digest than nitrate (Wetzel, 2001; Oktaviany et al., 2023). The higher nitrate concentration in the NB

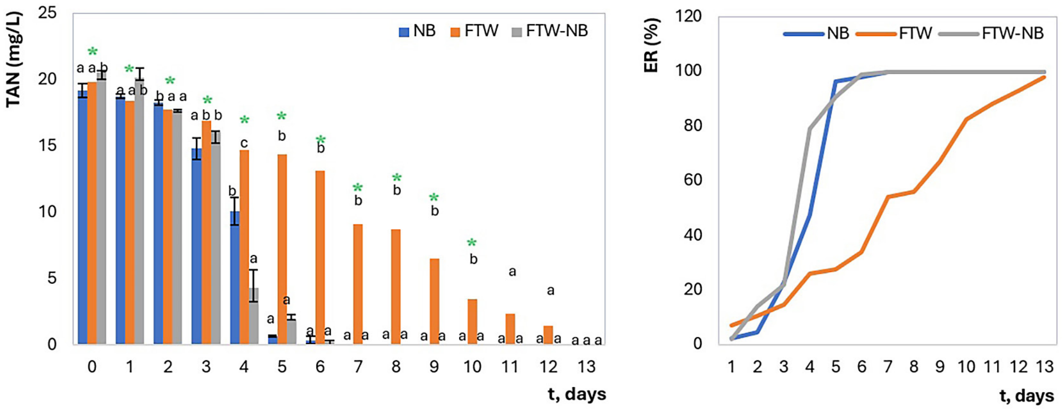

Figure 8. The concentration of TAN with * significant α = 0.05 and the notation of a, b, c for the Duncan test

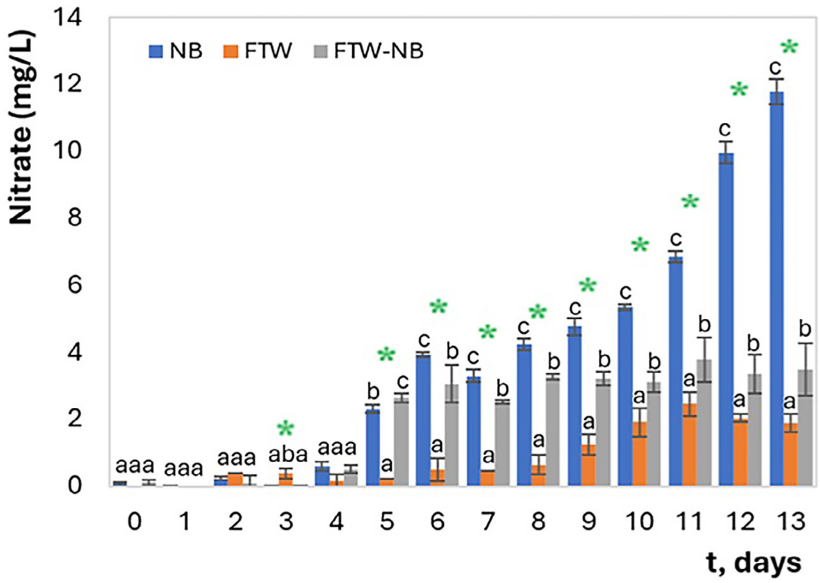

Figure 9. The concentration of nitrate, and the notation of a, b, c for the Duncan test

aeration system suggests that oxygenation encourages ammonium to undergo nitrification, which converts it to nitrate. However, the FTW-NB has lower nitrate concentrations than the NB system, indicating that vetiver actively absorbs nitrate and keeps it from accumulating in the water column.

The FTW's nitrate concentration increases more slowly than that of the FTW-NB, indicating that nitrification also takes place in the vetiver's root zone. This suggests that vetiver roots aid in the oxidation of ammonium to nitrate in addition to direct nitrate absorption, most likely due to related microbial activity in the rhizosphere. The findings show that although NB speeds up ammonium oxidation, vetiver in FTW improves nitrogen uptake and in situ nitrification, which helps the treatment system remove nitrogen overall.

The variations in total TN concentrations among the three treatment systems are depicted in the boxplot in Figure 10. With a larger data range and a higher median TN concentration, the NB indicates more performance variability. In contrast, the FTW system exhibits the lowest median TN concentration and the narrowest data range, suggesting a more consistent nitrogen reduction performance. The FTW-NB system combines the features of both treatments, yet its median TN concentration is comparable to the FTW system, with a slightly broader range, indicating some variability. Overall, while NB enhances oxygenation, FTW demonstrates the most stable and effective TN reduction, while combining the two systems (FTW-NB) does not appear to provide a significant advantage over FTW.

The total TN results reflect the combined impact of ammonia reduction and nitrate accumulation. FTW demonstrates the lowest TN concentration, implying strong nitrogen removal mechanisms such as plant uptake and denitrification. Although the NB and FTW-NB systems effectively reduce ammonia, their elevated nitrate levels contribute to higher TN concentrations overall. In conclusion, while NB and FTW-NB excel in rapid ammonia removal through effective nitrification, FTW provides the most stable and efficient total nitrogen reduction, likely driven by enhanced plant-based nutrient uptake and improved denitrification processes.

Ammonia removal was nearly complete across all systems, with NB and FTW-NB achieving

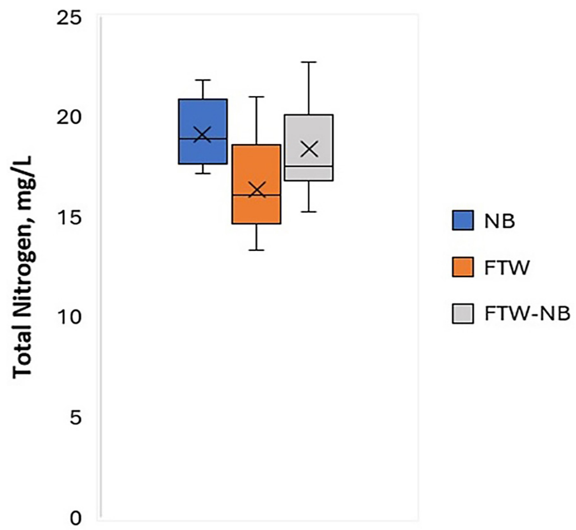

Figure 10. Concentration of total nitrogen

Table 4. Removal efficiency in each treatment

Parameter	Efficiency removal (%)			Information
	NB	FTW	FTW-NB	
Ammonia	100.00	97.86	100.00	NB 5, FTW-NB 6, FTW 13 (days)
TN	17.77	36.51	28.21	
Nitrate	+++	+	++	Increase in nitrate conc. due to ammonium oxidation
TSS	95.35	55.56	52.38	
DO average	7.35	1.46	6.94	DO increase with NB to > 8 on the second day

100% removal in 5 and 6 days, while FTW reached 97.86% efficiency over 13 days. This suggests that microbial nitrification and plant uptake played a significant role in ammonia reduction. However, total nitrogen (TN) removal was highest in FTW (36.51%), followed by FTW-NB (28.21%) and NB (17.77%), indicating that FTW is more effective at nitrogen retention through plant assimilation and microbial denitrification (Table 4). The qualitative assessment of nitrate removal (+++ for NB, ++ for FTW-NB, and + for FTW) suggests that nitrification was most pronounced in NB aeration due to enhanced oxygen availability, resulting in a higher accumulation of nitrate.

The NB system was most effective for TSS removal and nitrification, indicating that NB aeration enhances particle separation and ammonia oxidation through increased oxygenation. The removal efficiency of each parameter across the three treatment systems indicates that NB aeration significantly enhances DO levels in domestic wastewater, thereby promoting the oxidation of ammonia to nitrate. This effect is evident in the higher nitrate concentrations observed in the NB aeration system compared to the other two systems, confirming that oxygen availability accelerates the nitrification process.

CONCLUSIONS

This study shows that the removal of contaminants from domestic wastewater can be accomplished with different levels of efficiency using FTW, NB aeration, and their combination (FTW-NB). NB aeration significantly raised DO levels and accelerated ammonia oxidation to nitrate. In both systems, FTW-NB and NB aeration, NB played the most significant role in ammonia reduction, reaching 100% on days 5-6. FTW demonstrated the highest TN efficiency. On the other hand, the NB system removed the most TSS, most likely due to coagulation and flotation effects. FTW-NB achieved a balance between improved oxygenation and plant-mediated absorption of pollutants. For the best domestic wastewater treatment, this study emphasized the significance of combining biological and physical treatment techniques. Increased oxygen availability, microbial activity, pollutant elimination, ammonia oxidation, and plant growth are all benefits of NB aeration. Through domestic wastewater treatment, FTW is still the best technology, especially when it comes to reducing organic materials. To provide sustainable and efficient wastewater treatment, future research should optimize the integration of FTW and NB aeration by modifying aeration placement to avoid any disturbances in the plant absorption process.

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