Contribution of Newly Tested Species, Panicum maximum, for Faecal Sludge Treatment: A Comparative Study with Echinochloa pyramidalis and Typha domingensis

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Abstract

This study evaluated the effectiveness of three plant species (*Panicum maximum, Echinochloa pyramidalis*, and *Typha domingensis)*, in enhancing the removal of salinity, nitrogen, phosphorus, and chemical oxygen demand during sludge treatment within sludge treatment reed beds (STRBs). The experimental setup consists of 1 m^3 tanks composed of sand and gravel, simulating the reed bed configuration. A total of twelve pilot-scale units were used, with each plant species tested in triplicate, while three units were used as non-planted control groups. Over a six-month period, the units received weekly loadings of faecal sludge sourced from a site in southern Benin. Sampling was carried out weekly in order to evaluate the removal efficiency of the assessed parameters. The results showed the superior efficacy of STRBs compared to control beds, attributing this enhancement to the presence of vegetation. At a loading rate of 300 kg TS/m^2/yr, the system presented good performance. In particular, *Panicum maximum* and *Echinochloa pyramidalis* beds demonstrated the highest removal rates (Salinity: 97.95%, PO_4^{3-}: 97.75%, TP: 98.08%, NH_4^+: 98.68, NO_3^-: 98.71%, TKN: 99.53%, TSS: 99.98%, COD: 99.94%). Moreover, the drying rates of *Echinochloa pyramidalis* and *Panicum maximum* beds (49.5% and 48.5%, respectively) surpassed those of *Typha domingensis* beds (34.7%). These findings highlight the potential of *Panicum maximum*, a newly tested species, for application in STRBs, emphasizing the need for dedicated research on this species.

Introduction

In low-income countries, the application of sludge treatment reed beds (STRBs) has emerged as a promising solution for the effective treatment of faecal sludge (Ingallinella et al., 2002; Seck et al., 2015). Originally employed in Europe for urban wastewater dewatering and stabilization, these beds have garnered recognition as a reliable technique for African nations. With minimal energy demands and cost-efficient operation and maintenance, they offer economic advantages (Uggetti et al., 2010). Additionally, these reed beds hold potential for resource recovery by using plants for animal feed and treated faecal sludge for soil enrichment, resulting in revenue generation (Kengne and Tilley, 2014; Sloan et al., 2016). The role of vegetation in the dewatering and stabilization of sludge within these reed beds is paramount, involving intricate mechanisms such as evapotranspiration and the biochemical activation of the microbial population in the root zone (Hu et al., 2017). Although extensively applied in wastewater treatment, adapting reed beds for faecal sludge poses greater challenges due to its high variability and elevated concentrations of organic matter and nutrients, which can be 10 to 100 times higher than those found in wastewater (Niwagaba et al., 2014). Consequently, specific research is imperative to customize the technology, especially for local contexts in developing countries, through the incorporation of indigenous plant species (Goussanou et al., 2023).

Past studies have concentrated on tailoring STRBs to tropical climates (Kengne et al., 2008; Kouawa et al., 2015; Gueye et al., 2016). Among the existing literature, *Echinochloa pyramidalis* stands out as a dependable species for faecal sludge treatment in tropical climates, given its treatment efficiency and economic advantages for resource and cost recovery (Goussanou et al., 2023). Research reveals that *E. pyramidalis* yields between 5 and 8 tons of fresh weight of marketable forage daily during both dry and rainy seasons, with prices ranging from USD 0.1–0.2 to USD 0.2–0.3 per kg of fresh weight, leading to daily earnings of USD 800–1600 and USD 500–1500 during the rainy and dry seasons, respectively. Furthermore, *E. pyramidalis* showcases favorable nutritional attributes when employed in sludge treatment reed beds (Pare et al., 2012).

However, consideration of local availability and feasibility is crucial when selecting a suitable species. In Benin, *Panicum maximum* emerges as a promising contender among native species, exhibiting significant potential for faecal sludge treatment. It shares several traits with *Echinochloa pyramidalis* while offering supplementary advantages, such as resistance to rapid fires without compromising underground roots and drought tolerance due to its profound, dense, and fibrous root system. Additionally, *Panicum maximum* has a high protein content (5-5.6% fresh weight) with 88% digestibility (Aganga and Tshwenyane, 2003) and is highly valued as cattle forage (Odedire and Babayemi, 2008). Its application as forage in Benin spans several years (Aboh, 1999), and it has demonstrated efficacy in wastewater treatment, achieving removal rates of 100%, 93%, 94%, 68%, and 63% for total suspended solids (TSS), chemical oxygen demand (COD), five-day biochemical oxygen demand (DOB_5), Total Kjeldahl nitrogen (TKN), and total phosphorus (TP), respectively (Deguenon, 2014). Furthermore, other studies have investigated the performance of *Panicum maximum* and recommended its suitability for use in wastewater treatment via planted filter beds (Ouattara et al., 2011; Dhulap et al., 2012; Palta Prado and Morales Velasco, 2013). This study aims to assess the growth capabilities and faecal sludge treatment efficiency, of *P. maximum*, a species previously unexplored in the context of sludge treatment reed beds. This study also evaluates the performance of this species under increased faecal sludge loading rates and compares it with the performances of *E. pyramidalis* beds, *T. domingensis* beds, and unplanted beds.

Materials and Methods

1.1 Study area and plant origin

This study was conducted in the southern region of Benin, which is characterized by a tropical climate with an average annual rainfall of 1342 mm and an average yearly temperature of 27°C. Three distinct macrophyte species, namely *Echinochloa pyramidalis, Typha domingensis*, and

Panicum maximum, were chosen as the macrophytes for this investigation. These macrophytes were obtained from diverse locations within the study area. Subsequent to the collection, the harvested macrophytes underwent defoliation and were immersed in water to prevent excessive desiccation prior to their introduction into the sludge treatment reed beds. Cuttings derived from the harvested plants were then transplanted into the beds at a density of twelve (12) cuttings per square meter (12 cuttings/m^2). The experimental phase of this research was carried out at the Laboratory of Water and Environmental Sciences and Techniques, University of Abomey-Calavi (Benin).

1.2 Experimental setup

The configuration employed for the sludge treatment reed beds in this study adhered to a specific design (Fig. 1). The system consisted of 1 m^3 tanks interconnected with 250 L drums designed for percolate accumulation. The beds were carefully constructed with a layered design, starting from the topmost layer, which comprised a 15 cm stratum of coarse sand ($0.25 \leq d_{10} \leq 0.40$; $3 \leq Cu \leq 5$; rolled material). This was succeeded by a layer of 10 cm of finely crushed gravel (4/6 mm), followed by a 15 cm layer of moderately crushed gravel (15/25 mm), and concluding with a 15 cm layer of coarsely crushed gravel (30/60 mm) (Fig. 2). For optimal air circulation, a ventilation system was incorporated, featuring two PVC pipes with a diameter of 100 mm. In the lower section of this system, approximately 25 mm wide slots were strategically placed at 50 mm intervals. These slots were interconnected with two chimneys, facilitating improved airflow within the filtration bed (Fig. 2). The entire assembly was meticulously finalized using interlocking and adhesive techniques, and it was diagonally positioned within the beds. To collect the percolates, a slight slope was created in the bottom to direct them towards a 250 L drum through a 250 mm diameter PVC pipe equipped with a valve.

Figure 2: **Photographs of the experimental setup**

A total of twelve (12) sludge treatment reed beds were used in this experimental setup, with each plant species having triplicate setups, and an additional triplicate bed serving as the control group. The planting density was set at 12 cuttings/m^2. The selection of the number of beds ensured a minimum of three replicates for each treatment, meeting the necessary criteria for robust statistical analysis. The determination of planting density also took into account previous research recommendations (Edwards et al., 2001; Kengne et al., 2011). Upon planting, the beds were initially irrigated with borehole water to maintain saturation and prevent water stress during the critical growth phase of the plants. Subsequent watering was conducted once a week using a mixture of borehole water and a small amount of sludge, providing essential nutrients for plant growth. To acclimatize the plants gradually to increasing sludge loads, considering their developmental stage, the sludge loads were incrementally raised in steps of 100, 150, 200, and 300 kg/m^2/year of total solids (TS) during a two-month ramp-up phase. Following this phase, a nominal phase with a constant load of 300 kg/m^2/year of total solids (TS) was initiated (Table 1). Subsequently, the beds were left undisturbed for approximately two months to assess the dewatering level of the biosolids.

Table 1
Evolution of loads across different experimental phases

	Acclimatation phase						**ramp-up phase**								**Nominal phase**					
Time (Week)	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Loads (kg TS/m^2/year)	20	30	40	50	60	70	90	120	150	180	210	240	270	300	300					

1.3 Monitoring plant growth dynamics

Morphometric parameters, including average sizes and average densities, were meticulously recorded to assess the growth and development of plants within the STRBs. Size measurements were obtained by employing a tape measure to determine the distance from the base of the plants, in direct contact with the sludge layer, to the apical part of the plants. To ensure comprehensive data collection, a stratified sampling approach was employed, stratifying the plants into three size categories: small, medium, and large. Plant density, an essential parameter reflecting the population of plants within the beds, was determined by meticulously counting the number of stems per bed. This enabled a quantitative assessment of the plant population and offered valuable insights into the dynamics of plant growth within the STRBs. To capture the intricate nuances of plant development, these morphometric measurements were performed on a weekly basis, enabling the comprehensive tracking of plant growth and development over time.

1.4 Faecal sludge characterization

The concentrations of various pollutants, including Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Ammonium (NH_4^+), Nitrates (NO_3^-), Total Kjeldahl Nitrogen (TKN), Total Phosphorus (TP), and Orthophosphates (PO_4^{3-}), were quantified in both raw sludge and leachate samples using established protocols outlined in APHA-AWWA-WEF (2005). Each sampling event involved collecting three replicates, and the mean values were used for subsequent analysis. Furthermore, the pH, conductivity, Total Dissolved Solids (TDS) and salinity of the raw sludge and leachate samples were directly measured using a handheld multi-parameter VWR MU 6100 H. The purification efficiency was assessed based on various physicochemical parameters, including TSS, COD, TP, NH_4^+, NO_3^-, TKN, and PO_4^{3-}. To ensure accuracy and control for any potential errors, the leachate was collected 24 hours after feeding.

1.5 Statistical analysis

The Kruskal-Wallis one-way analysis of variance test, which is a non-parametric way to compare more than two groups, was used for statistical analysis. This was followed by a thorough multiple pairwise comparison procedure using the Dunn test. The Kruskal-Wallis test allows for the detection of differences among treatment groups without requiring the assumptions of a normal distribution. Subsequently, the Dunn test facilitates a detailed exploration of variations among the treatment groups, providing valuable insights into the specific performance distinctions of each treatment relative to the others. These non-parametric methods were particularly advantageous in this study, as they are robust in handling data that may not conform to standard parametric assumptions, thus enhancing the reliability and relevance of our findings.

Results and Discussions

2.1 Characteristics of the faecal sludge

During this study, the sludge samples displayed the following mean values: pH of 7.5, salinity of 7.3, COD of 38837 mg/L, conductivity of 13 mS/cm, total dissolved solids (TDS) of 7.6, total suspended solids (TSS) of 62 g/L, nitrate (NO_3^-) of 250 mg/L, total phosphorus (TP) of 406 mg/L, orthophosphates (PO_4^{3-}) of 171 mg/L, and ammonium (NH_4^+) of 699 mg/L. These parameters served as the basis for evaluating the performance of the STRBs. Table 2 presents significant variations in all parameters, with the exception of pH. The wide range of domestic faecal sludge characteristics observed during this study aligns with findings from previous reports (Kengne et al., 2009; Osei et al., 2022). The sludges used in this research displayed significant salinity levels, and the high COD concentration observed is in line with typical values found in sanitation facilities in the West African region. It is imperative to underscore that the deliberate selection of highly concentrated sludge for this study enabled subjecting the plants to conditions of heightened extremity. Furthermore, Table 2 furnishes comparisons with previously reported values by Osei et al. (2022), Kouawa et al. (2015), and Troesch (2009), thereby situating the findings within a broader context and facilitating a nuanced interpretation of the observed trends during the course of this study.

Table 2
Characteristics of raw faecal sludges

	Mean ± SD	Min./Max.	Coeff. Var. (%)	Osei et al. (2022)	Tadjouwa Kouawa et al. (2015)	Troesch (2009)
pH	7.5 ± 0.23	7.1 / 7.9	3	7.91	9.1	7.2
TDS (g/L)	7.6 ± 2.1	5.1 / 11	27	2480	-	-
EC (ms/cm)	13 ± 3.4	8.3 / 18	27	4973	6.6	3
Sal (g/L)	7.3 ± 2.1	4.7 / 10	28	-	-	-
NO_3^- (mg/L)	250.2 ± 116.2	105.1/638	9.6	10	84.4	
NH_4^+ (mg/L)	699 ± 230	416 / 974	33	390	328	302
TKN (mg/L)	3029 ± 568	2644 / 4271	19	-	-	-
PO_4^{3-} (mg/L)	171 ± 87	97 / 331	51	60	51.9	46
TP (mg/L)	406 ± 186	160 / 648	46	3930	172	699
TSS (g/L)	62 ± 7.9	45 / 70	13	18.28	1.53	28.15
COD (mg/L)	38837 ± 15872	19200 / 57600	41	1345	4672	47051

Considering the well-established impact of high salinity on plant physiology, diligent monitoring of this parameter is essential in STRBs. The detrimental effects of high salt stress affect multiple critical stages of a plant's life cycle, including seed germination, seedling development, vegetative growth, flowering, fruit set, and root system architecture. The disruption of ionic equilibrium and water stability under salt stress conditions significantly impairs plant growth and, ultimately, leads to plant mortality (Liang et al., 2018). Therefore, meticulous assessment and management of salinity levels in the growth environment are imperative to ensure optimal plant performance and maximize treatment efficiency in sludge treatment reed beds.

2.2 Dynamics of plant development over time

The growth response of each plant species to incremental additions of faecal sludge in STRBs was investigated by continuously monitoring changes in average size and density throughout the duration of the study. This approach provided a comprehensive assessment of the growth potential demonstrated by each species under the challenging and unfavorable conditions encountered in STRBs. By closely observing the fluctuations in average size and density of the plants as the faecal sludge loads increased, valuable insights were obtained regarding the adaptability and performance of each species within the specific context of STRBs.

2.2.1 Plant height dynamic

The growth of plants in terms of height was continuously monitored throughout the experimental period. By the study's conclusion, notable variations in performance had become evident among the different plant species. *Panicum maximum* had a significantly higher level of performance during the nominal phase in comparison to the other two species, particularly when compared to *T. domingensis* (*p = 0.0001*; Fig. 4). Also, there was no significant difference between how well *Echinochloa pyramidalis* and *Typha domingensis* grew (*p = 0.1284*; Fig. 4). The mean heights of *Typha domingensis, Echinochloa pyramidalis*, and *P. maximum* during the nominal phase of the investigation were measured as 2.203 ± 0.133 m, 2.466 ± 0.083 m, and 2.72 ± 0.114 m, respectively (Fig. 3).

2.2.2 Plant density dynamic

In the sludge treatment reed beds, the density of plants gradually increased as a result of vegetative reproduction for all species. Initially planted at a density of 12 cuttings/m^2, *Typha domingensis, P. maximum*, and *Echinochloa pyramidalis* exhibited a progressive increase in density from 34 ± 02, 31 ± 03, and 35 ± 06 plants/m^2, respectively, during the acclimation period to 95 ± 14, 111 ± 01, and 122 ± 03 plants/m^2, respectively, by the end of the ramp-up phase. At the conclusion of the experiment, the densities were recorded as 93 ± 32, 138 ± 03, and 143 ± 10 plants/m^2 for *Typha domingensis*, *P. maximum*, and *Echinochloa pyramidalis*, respectively. (Fig. 5)

Statistical analysis revealed significant differences among the three treatments, particularly between *E. pyramidalis* and *T. domingensis* (*p = 0.0005*), as well as between *P. maximum* and *T. domingensis* (*p = 0.0310*). *Echinochloa pyramidalis* and *Panicum maximum* exhibited similar growth patterns and showed no significant difference between them (Fig. 6). These findings suggest that both *Echinochloa pyramidalis* and *Panicum maximum* exhibited a higher multiplication rate compared to *Typha domingensis*. This observation underscores their potential for rapid expansion and colonization, particularly under the stress conditions imposed by faecal sludges within the STRBs. It is worth noting that plants of this nature possess the capacity for vegetative propagation through structures such as rhizomes, adventitious roots, and stolons, thereby contributing to an overall increase in plant density within STRBs (Hutchinson et al., 1954).

Figure 6: **Comparison of average density among macrophytes during the nominal phase**

The observed outcomes can be attributed to the combined effects of genetic traits inherent in plant species, the morphology of their rhizomes, and the specific capabilities of the rhizospheric microbiome of each plant (Bart and Hartman, 2003; Man et al., 2020; Wang et al., 2021; Koza et al., 2022). Moreover, since the underground part of these plants is the component most exposed to pollutants, it must possess the capability to extract the necessary nutrients under these challenging conditions. This plant portion provides an ideal attachment point for the colonization and proliferation of microorganisms, resulting in higher microbial density and activity. This microbial activity plays a pivotal role in sludge mineralization and efficient water and nutrient absorption (Gagnon et al., 2007; Jacoby et al., 2017). Nevertheless, each species exhibits predispositions that favor the development of specific categories of microorganisms. Consequently, each plant species possesses its own unique microbiome, which contributes to a specific growth dynamic depending on environmental conditions.

The choice of plant species used as macrophytes is the second most influential factor affecting microbial activity within planted beds, with the mere presence of plants being the primary influencing factor in this context. Furthermore, the developmental stage of the plant represents the third and final factor to consider (Wang et al., 2012). It is crucial to emphasize that both the presence of plants and the specific selection of plant species have significant impacts on various processes, including sludge dewatering, mineralization, and the quality of water exiting the beds (Gagnon et al., 2013).

2.3 Sludge dewatering efficiency

Except for the unplanted reed beds, the amount of percolate recovered remains below 50% of the applied volume, regardless of the plant species (Fig. 7). Previous studies by Stefanakis and Tsihrintzis (2011) have indicated that evapotranspiration is the primary mechanism responsible for water loss in planted beds, while percolation plays a more prominent role in water loss within unplanted beds, resulting in larger volumes of percolate.

Furthermore, the percentages of percolate collected in *E. pyramidalis* and *P. maximum* beds (12.15% and 12.74%, respectively) are lower than those collected in *Typha domingensis* beds (34.77%). This observation suggests that *E. pyramidalis* and *P. maximum* plants exhibit a higher evapotranspiration rate, leading to greater water removal compared to *Typha domingensis*. It is important to note that comparative studies on the evapotranspiration capacity of these three species are currently lacking in the existing literature. Previous investigations have primarily focused on the evapotranspiration characteristics of Typha species (Wang et al., 2009).

Figure 8: Photographs of the STRBs and their surfaces illustrating their dehydration levels during the nominal phase (A): T. domingensis; (B): P. maximum; (C): E. pyramidalis

Based on how quickly the *E. pyramidalis* and *P. maximum* beds dried out and their smaller percolate volumes, it was apparent that evapotranspiration was the main way water was lost. These two species, by their high evapotranspiration characteristics, exhibited significantly higher dryness rates compared to *Typha domingensis*. *E. pyramidalis* and *P. maximum* beds achieved dryness rates of 49.5% and 48.5%, respectively, while *Typha domingensis* beds attained a dryness rate of 31.6% (Fig. 7). This implies that *E. pyramidalis* and *P. maximum* release substantial volumes of water through evapotranspiration, reducing the risk of clogging and resulting in lower clogging rates in these beds. As sludge treatment reed beds aim to reduce and stabilize sludge volume, these findings highlight the favorable performance of *E. pyramidalis* and *P. maximum* in achieving this objective (Fig. 8). Moreover, previous studies have demonstrated a positive correlation between plant density and evapotranspiration rates (Bialowiec et al., 2007).

2.4 Pollution removal

Due to the treatment mechanisms occurring within the beds, residual pollutant concentrations observed in the percolates are significantly lower compared to the influent concentrations (Table 3). Furthermore, the average values observed in the leachates highlight the differences in abatement performances occurring within the various beds.

Table 3
Chemical parameters at the output of beds

Parameters	Control beds	*T. domingensis*	*E. pyramidalis*	*P. maximum*
pH	7.56 ± 0.09	7,43 ± 0.05	7.33 ± 0.03	7.41 ± 0.07
EC (mS/cm)	4.74 ± 1.58	4.68 ± 1.57	4.73 ± 0.74	2.25 ± 0.52
TDS (g/L)	4.28 ± 0.92	4.30 ± 1.04	4.26 ± 0.46	1.41 ± 0.36
Salinity (mg/L)	2.51 ± 0.68	1.96 ± 0.87	2.13 ± 0.32	1.17 ± 0.34
NO_3^- (mg/L)	149.6 ± 8.99	90.36 ± 5.67	89.78 ± 11.86	76.31 ± 15.57
NH_4^+ (mg/L)	105.1 ± 51.67	117.0 ± 61.44	75.48 ± 50.20	90.31 ± 49.52
TKN (mg/L)	533.3 ± 62.21	151.5 ± 61.41	99.75 ± 50.67	111.5 ± 38.16
PO_4^{3-} (mg/L)	95.33 ± 27	87.11 ± 54.90	31.57 ± 1.63	47.71 ± 14.41
TP (mg/L)	219.9 ± 39.57	111.7 ± 54.42	116.5 ± 71.79	60.86 ± 37.70
TSS (g/L)	0.28 ± 0.11	0.13 ± 0.11	0.16 ± 0.22	0.09 ± 0.08
COD (mg/L)	585.5 ± 178.0	287.5 ± 55.41	444.3 ± 42.01	161.0 ± 29.14

The assessment of pollutant removal efficacy based on input and output flux changes has demonstrated STRB's performance. STRBs remove a variety of pollutants through physical processes such as filtration, adsorption, sedimentation, particulate interception by plant roots, and precipitation (Dhir, 2013). The observed removal rates in this study for TSS all exceed 99.73%. Due to the high proportion of coarse particles, TSS are retained at the surface of STRBs (Wang et al., 2009; Dhir, 2013). The removal of TSS through these physical processes also leads to the reduction of COD, nitrogen, and phosphorus through the physical retention of particulate forms of these pollutants (Kuffour et al., 2009). The organic load removal performance, as assessed through COD concentration levels, achieved good results with reductions of 99.94% for *P. maximum*, 99.86% for *E. pyramidalis*, 99.74% for *T. domingensis*, and 99.12% for the control beds (Fig. 9). These findings align with previous studies by Kengne et al. (2009), which reported a COD reduction of 95% with *Echinochloa pyramidalis* STRBs. The presence of particulate components in the sludge predominantly contributes to the high depollution rates through physical filtration via the filtering media. Furthermore, the symbiotic relationship between plants and microorganisms within the network of rhizomes plays an important role in achieving these depollution rates (Wang et al., 2009; Korboulewsky et al., 2012). Depending on their location within the bed and the availability of oxygen, these microorganisms facilitate both aerobic and anaerobic degradation processes (Chazarenc and Merlin, 2005).

Effective nitrogen removal rates ranged from 95–98% for NO_3^-, 98–99% for TKN, and 94–98% for NH_4^+ across all sludge treatment reed beds. These findings underscore the significant role of plants in nitrogen pollution mitigation, particularly in the removal of NO_3^- and NH_4^+ through plant uptake. These removal mechanisms involve a combination of plant absorption and various biochemical processes such as adsorption, ammonification, nitrification, and denitrification (Saeed and Sun, 2012). The range of phosphorus abatement rates observed in this study STRBs ranged from 82–96% for PO_4^{3-} and from 90–98% for TP (Fig. 9). The better removal performances observed in comparison with temperate regions can be attributed to the hot temperatures prevalent in tropical countries, which stimulate the metabolic activity of plants and microorganisms as well as organic matter and nutrient transformations. These factors contribute to enhanced treatment outcomes compared to planted beds implemented in temperate regions for sludge treatment (Uggetti et al., 2009, 2012; Brix, 2017; Nielsen and Stefanakis, 2020).

Apart from COD and TSS, the unplanted beds exhibit lower removal efficiencies compared to the planted beds, with statistically significant differences ($p < 0.05$). In fact, regardless of the plant species, be it *T. domingensis, E. pyramidalis*, or *P. maximum*, and regardless of the parameter assessed, removal rates consistently exceed 80%. *E. pyramidalis* and *P. maximum* demonstrate superior removal efficiencies compared to beds planted with *T. domingensis* and the unplanted beds. Specifically, they exhibit closely matched removal efficiencies for several parameters, except for TDS, salinity, and TP. In the cases of TDS, salinity, and TP, *P. maximum* achieves the highest removal rates, with respective rates of 97%, 97%, and 98%.

2.4.1 Ionic quality of sludge and percolates

The pH stands out as one of the few parameters where no significant difference is noted between the values recorded in the raw sludge and the leachates in this study (Fig. 10). This observation implies that the sludges under investigation in this study exhibited suitable conditions conducive to biological activity. Furthermore, at the outlet, the neutral conditions of the input sludges were upheld in the discharged leachates. However, regarding conductivity, a significant difference exists among the average values observed in the leachates from the various beds. These differences underscore the implementation of both mechanical and microbiological treatment processes within the beds. Indeed, it has been demonstrated that certain symbiotic microorganisms in the plant's underground parts mitigate the adverse effects of elevated electrical conductivity by restricting excessive sodium (Na^+) entry into the cells while promoting potassium (K^+) absorption. This contributes to the plant's resilience and growth under such stressful conditions (Wang et al., 2019).

2.4.2 Suspended and dissolved content removal

The results of this study reveal a significant difference in total suspended solids (TSS) removal between beds planted with *P. maximum* and non-planted control beds ($p = 0.0335$), further emphasizing the positive impact of plant presence on TSS removal efficiency. The results across different planted beds showed comparable levels of reduction ($p > 0.05$) (Fig. 11). This suggests that the presence of plants, regardless of the species used, contributes to the removal of TSS. The development of the root network plays a vital role in optimizing the mechanical filtration process, facilitating the separation of solid and liquid phases. Aside from suspended solids, dissolved substances play a crucial role in STRBs. It has been observed that total dissolved solids (TDS) are reduced by over half in all beds, with the lowest concentrations found in the percolates of *P. maximum* beds, exceeding an 80% reduction in terms of concentration. Moreover, within the scope of this study, TDS mainly comprises Na^+ and Cl^- ions, with a [Salinity/TDS] ratio of 0.96. Salinity stands out due to its high prevalence in faecal sludge, and its negative impact on plant development, resulting in slower growth and stunted plants (Bernstein, 1975; Kumar et al., 2023). The input sludges had an average salinity of 7.30, and *Panicum maximum* demonstrated remarkable resilience to such conditions. Notably, the beds planted with *Panicum maximum* exhibited the highest rates of salinity removal in the collected percolates, with average values of 1.17, 2.13, and 1.96 for *Panicum maximum, Echinochloa pyramidalis*, and *Typha domingensis*, respectively (Table 3).

–Figure 11: Removal of (a) TSS, (b) TDS, (c) Salinity

These findings highlight the resilience of *Panicum maximum* to high-salinity sludge and its good performance in sludge treatment reed beds. The comparisons between these three plant species used in this study revealed significant differences, with *Panicum maximum* exhibiting superior performance compared to the other two species as well as the control bed (Fig. 11). Despite the wide variety of macrophyte species, only a select few are capable of thriving in STRBs due to the unique conditions they present. These conditions include varying salinity and nutrient concentrations, as well as different growth environments ranging from anaerobic or anoxic to aerobic, depending on the feeding-resting cycle phases (Molle, 2012; De Maeseneer, 2018). The sludge used in this work represents typical latrine sludge, characterized by high pollutant concentrations. Additionally, in the context of this study, the sludge within the study area exhibits a gradient of salinity, ranging from moderate levels in instances of non-saline intrusion to elevated salinity levels in situations where saline intrusion occurs through the water table positioned at latrine level. While it has been clearly demonstrated that high salinity levels are the most detrimental factor for plant growth (Bernstein, 1975; Ahmad and Prasad, 2013; Ahmad et al., 2013; Liang et al., 2018). By subjecting the plants to such challenging conditions, this study aims to assess their performance under harsh circumstances.

2.4.3 Organic content removal

Significant reductions in chemical oxygen demand (COD) were consistently observed in all sludge treatment reed beds. Among the planted beds, *Panicum maximum* exhibited the highest removal efficiency, achieving a COD concentration reduction from 38837 mg/L in the raw sludge to 161 mg/L in the leachate. Statistical analysis indicated significant differences in performance between the various planted beds ($p < 0.0001$)

(Fig. 12). It is important to highlight that, despite the effective abatement performance, additional treatment processes are necessary to refine the leachates before their discharge into the natural environment.

2.4.4 Nutrients content removal

Effluent nutrient content was assessed, focusing on mean concentrations of nitrogen compounds and phosphorus. A general decrease was observed for all monitored parameters (Table 3). Overall, a comparative analysis of *E. pyramidalis* and *P. maximum* planted beds revealed similar reduction performances for all parameters related to phosphorus and nitrogen ($p > 0.05$). The performance of *P. maximum* planted beds was found to be significantly higher than that of control beds for TKN, NO_3^-, and TP, as indicated by the obtained *p*-values of *0.0062, 0.0003*, and *0.0005*, respectively. Regarding nitrogen removal, the lowest concentrations in the percolates were achieved either by the *E. pyramidalis* planted beds or the *P. maximum* planted beds, with values of 76.31 mg/L for NO_3^-, 75.45 mg/L for NH_4^+, and 99.75 mg/L for TKN (Fig. 13). Significant reductions in phosphorus concentrations were noted in different bed leachates. The initial average orthophosphate concentration of 171.33 ± 87.27 mg/L decreased in the leachates of *Echinochloa pyramidalis, Panicum maximum, Typha domingensis*, and unplanted beds, with average concentrations of 31.57 ± 1.63 mg/L, 47.71 ± 14.41 mg/L, 87.11 ± 54.90 mg/L, and 95.33 ± 27 mg/L, respectively. Similarly, for total phosphorus concentrations, initial concentrations in the sludge of 406.5 ± 186.5 mg/L decreased to 60.86 ± 37.70 mg/L, 116.5 ± 71.79 mg/L, 111.7 ± 54.42 mg/L, and 219.9 ± 39.57 mg/L in *Echinochloa pyramidalis, Panicum maximum, Typha domingensis*, and unplanted beds, respectively (Fig. 14).

Conclusion

This research emphasizes the efficacy of sludge treatment reed beds, with a specific focus on the use of the indigenous macrophyte *Panicum maximum*, in the context of treating faecal sludge. Notably, *P. maximum* has demonstrated remarkable efficacy in pollutant reduction, similar to *Echinochloa pyramidalis*. The focal point here is that, unlike *E. pyramidalis*, *P. maximum* had not previously been tested for faecal sludge treatment. Furthermore, beyond demonstrating comparable performance to the previously tested plant, it exhibits superior performance in certain parameters, such as salinity, which is a key abiotic factor contributing to plant mortality.

However, it's crucial to acknowledge that further refinement treatments are necessary before the treated sludge can be safely discharged into the natural environment. This points to the need for future research in several directions. First, the scalability of *Panicum maximum* in STRBs at full scale and its long-term effectiveness should be evaluated. Second, investigations should delve into elucidating the precise mechanisms by which *P. maximum* achieves higher salinity reduction levels, highlighting the combined mechanisms responsible for such performance. These areas warrant attention in future studies to advance our understanding and application of this promising plant species in sludge treatment reed beds.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Baruc Kpèhouénou Goussanou, Akuemaho Virgile Onésime Akowanou, Mouhamadou Nourou Dine Liady, and Olouwachêgun Esdras Moïse Ayitchédéhou . And The first draft of the manuscript was written by Baruc Kpèhouénou Goussanou and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

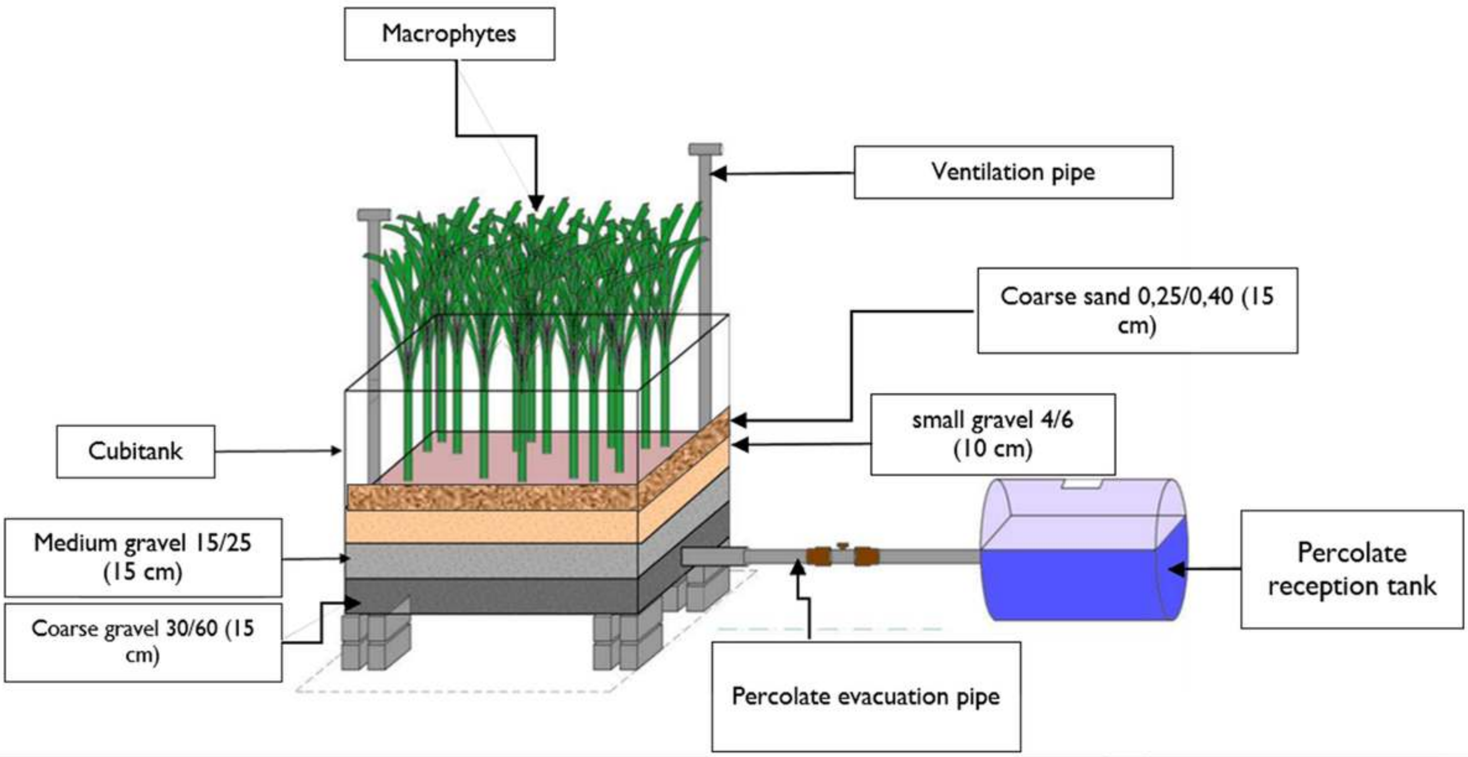

Figure 1

Illustration of the STRBs implemented in this study

Figure 2

Photographs of the experimental setup

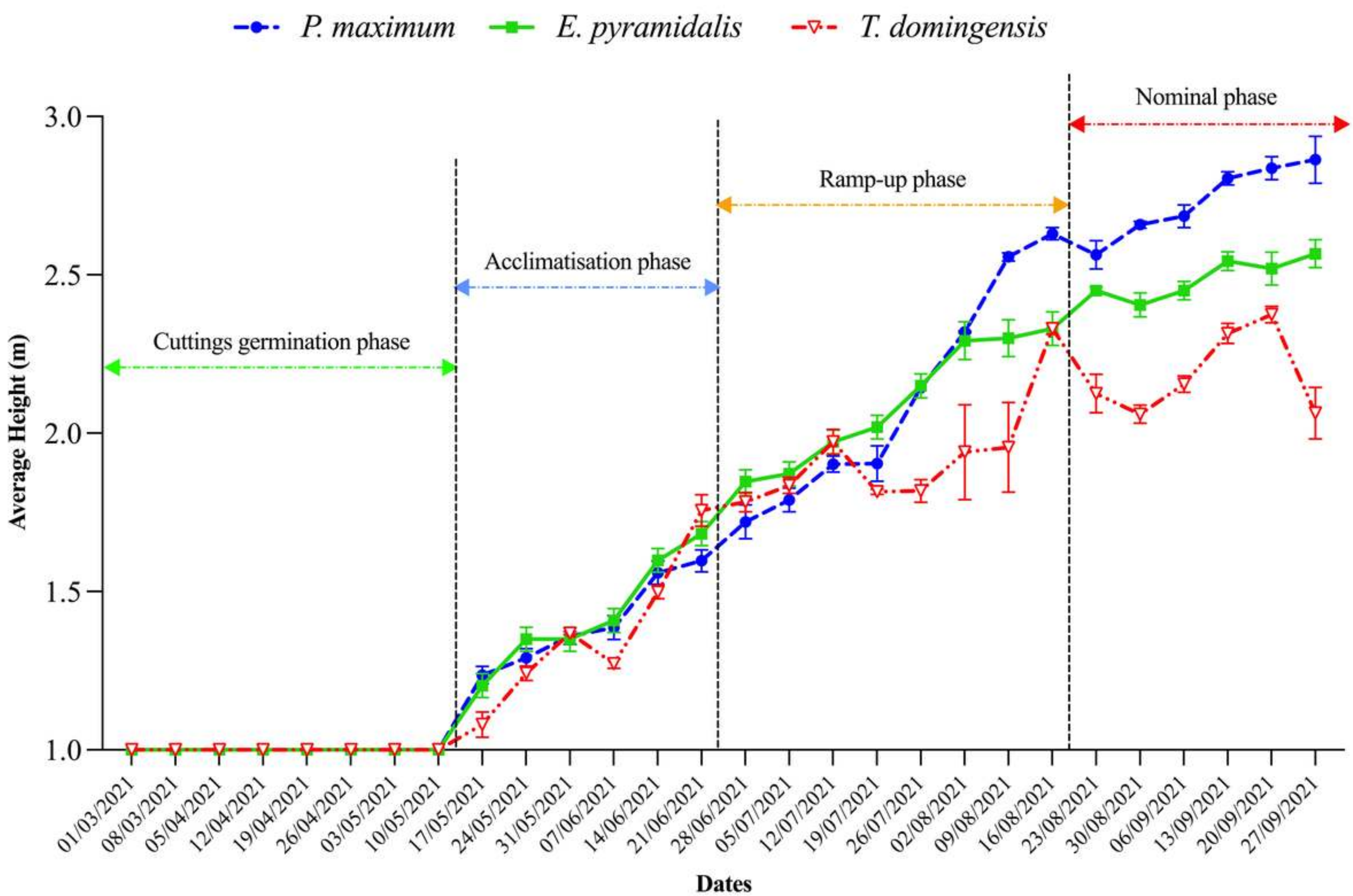

Figure 3

Evolution of average height over time

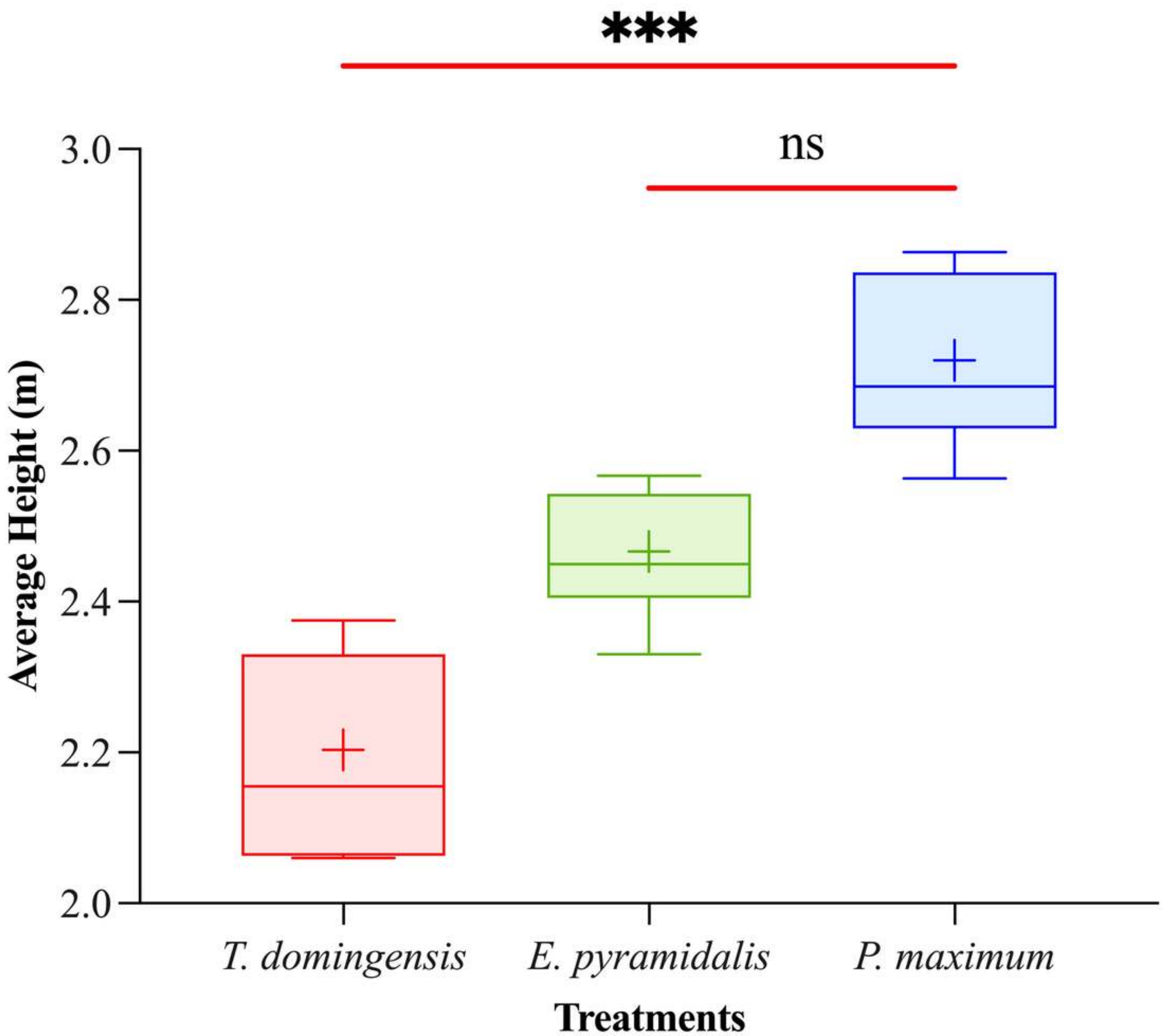

Figure 4

Comparison of average height among macrophytes during the nominal phase

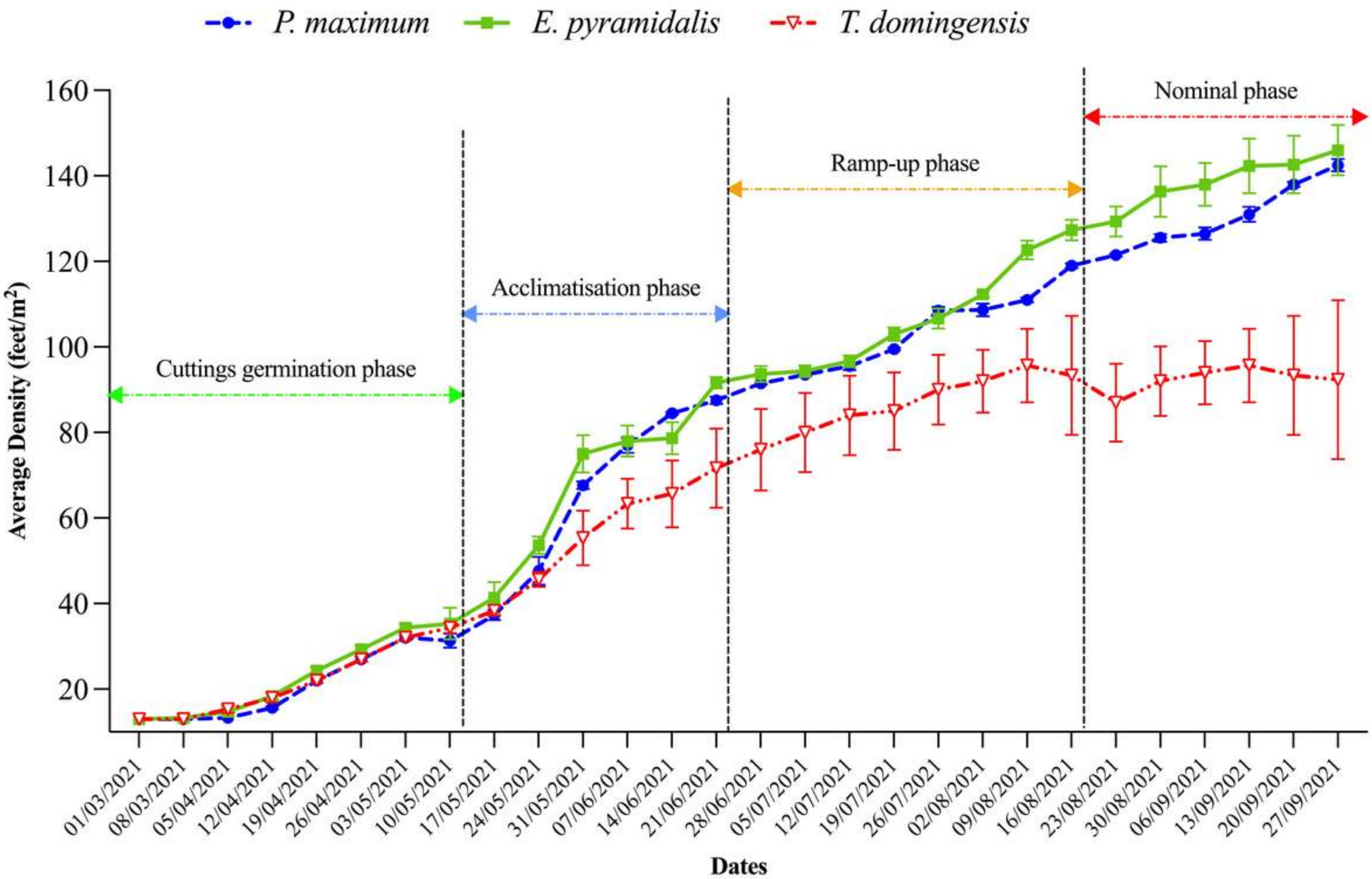

Figure 5

Evolution of average density over time

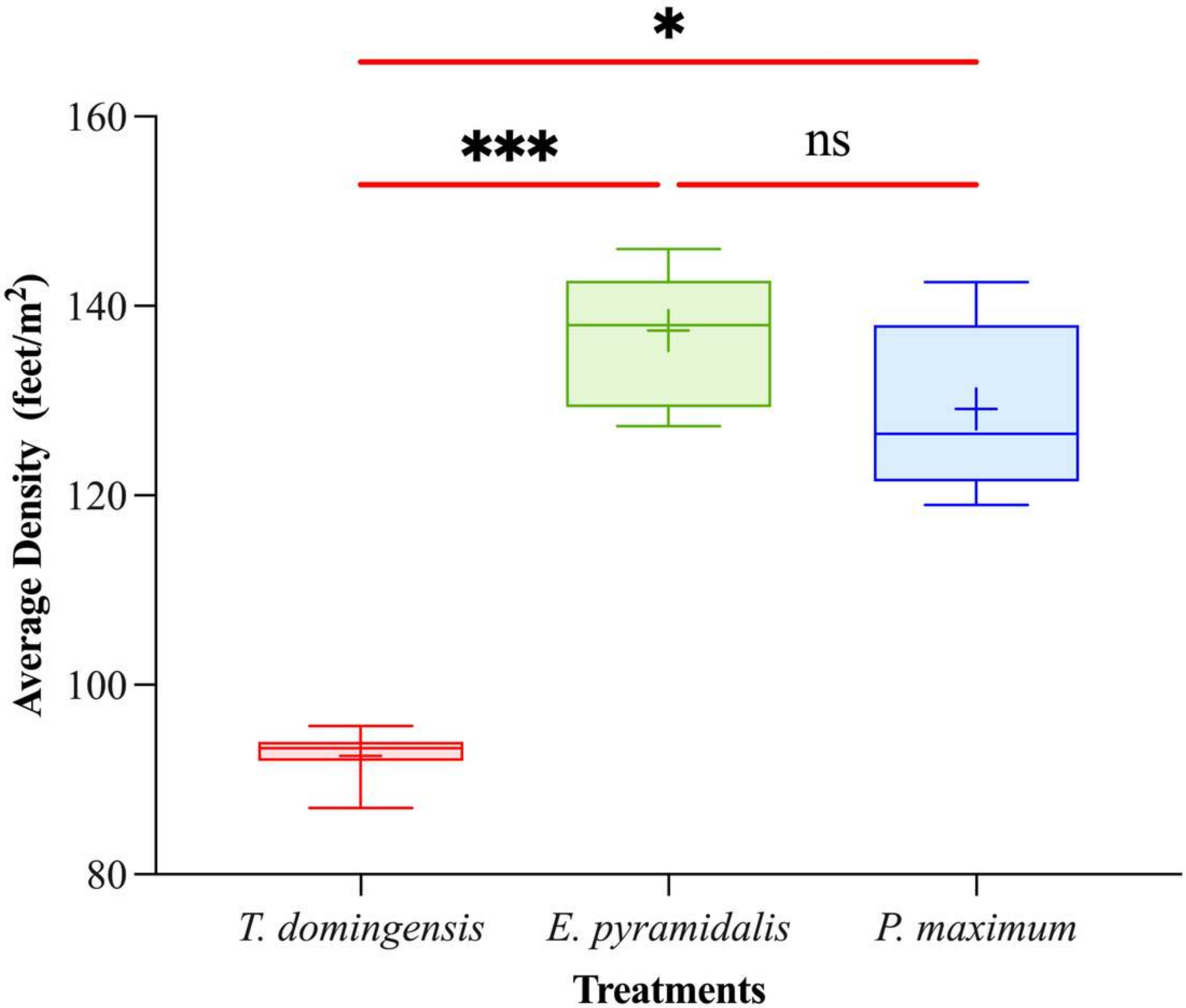

Figure 6

Comparison of average density among macrophytes during the nominal phase

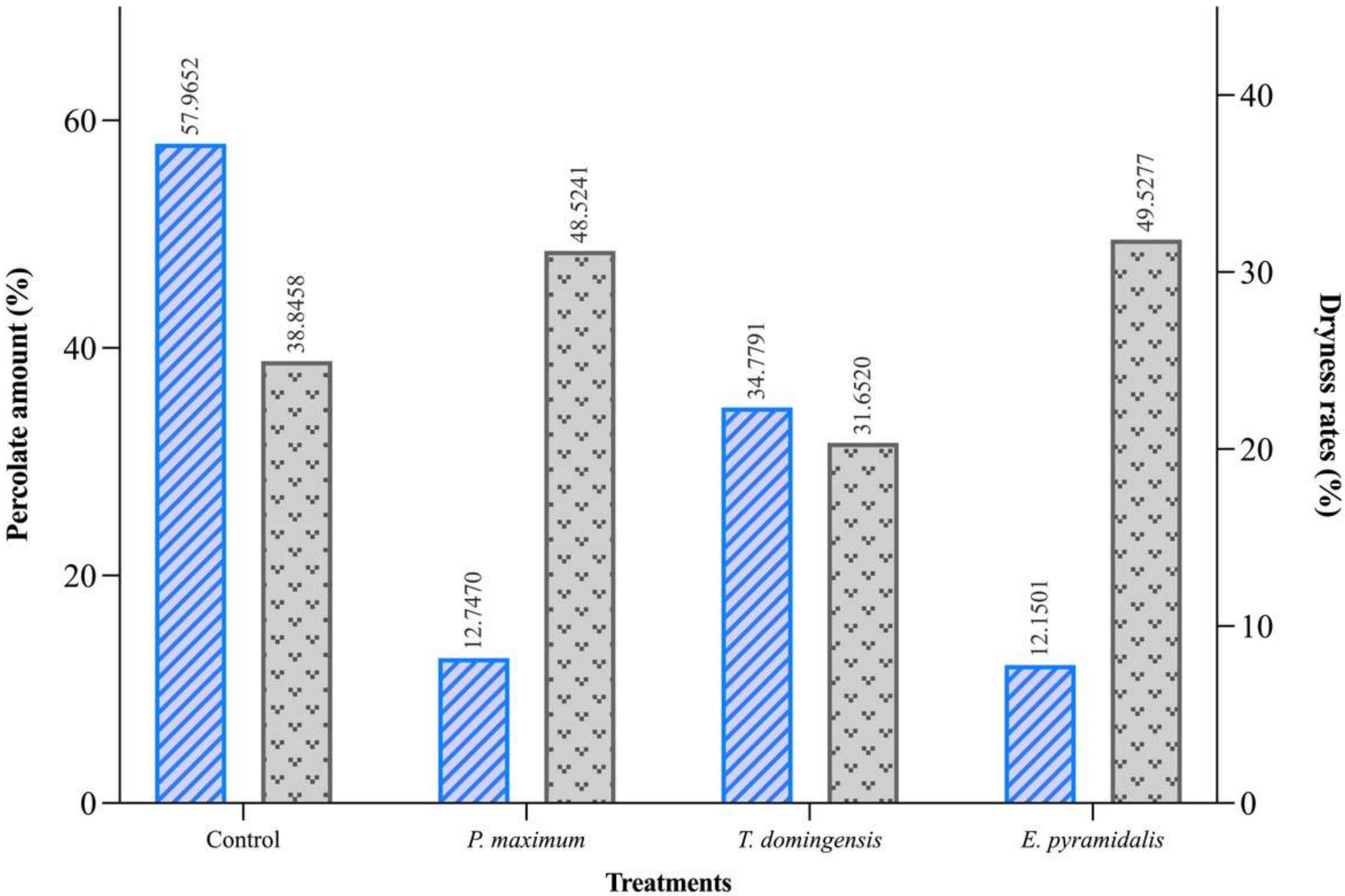

Figure 7

Percolate amount and dryness rate of STRBs

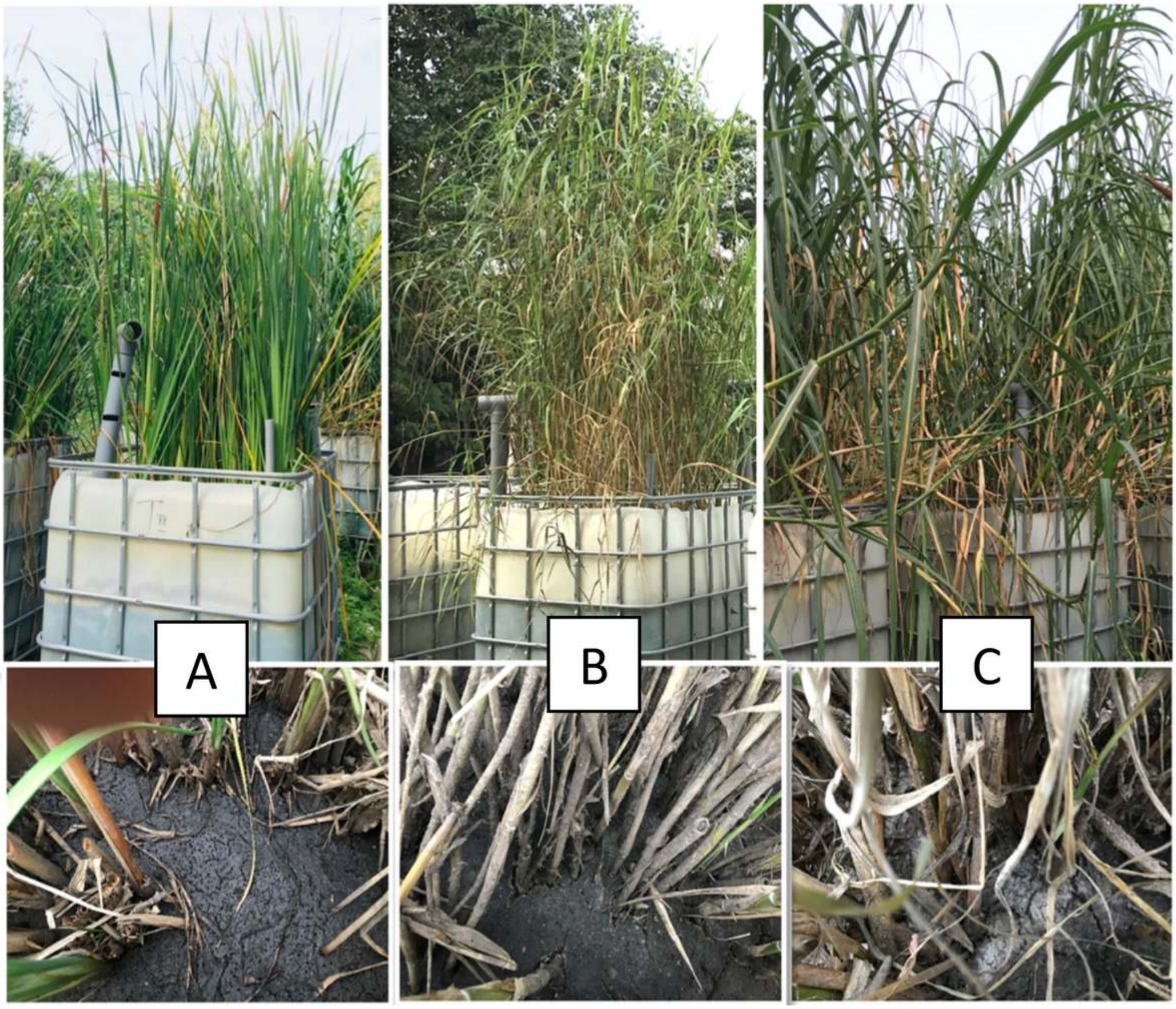

Figure 8

Photographs of the STRBs and their surfaces illustrating their dehydration levels during the nominal phase (A): *T. domingensis*; (B): *P. maximum*; (C): *E. pyramidalis*

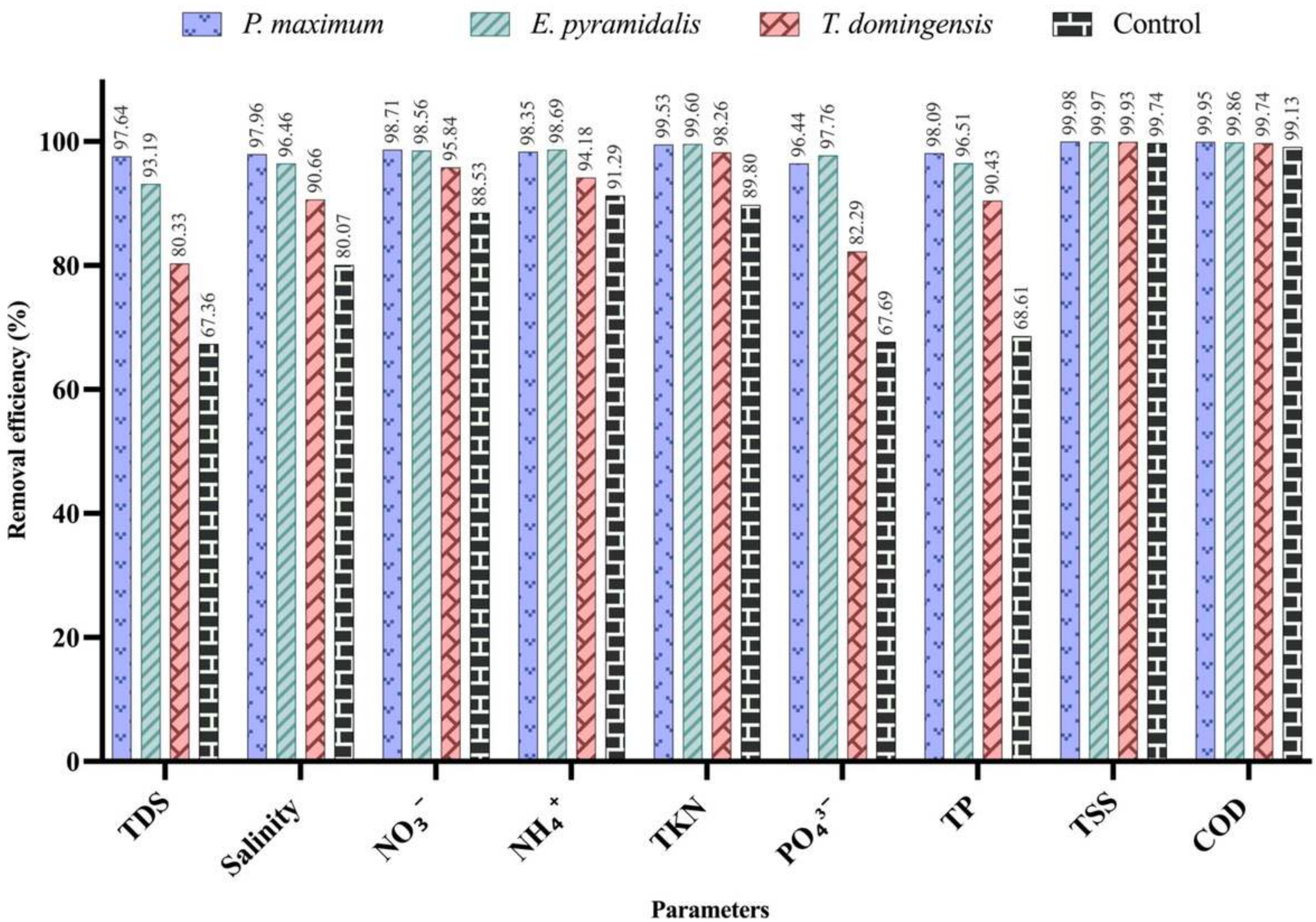

Figure 9

Summary of Removal Performance

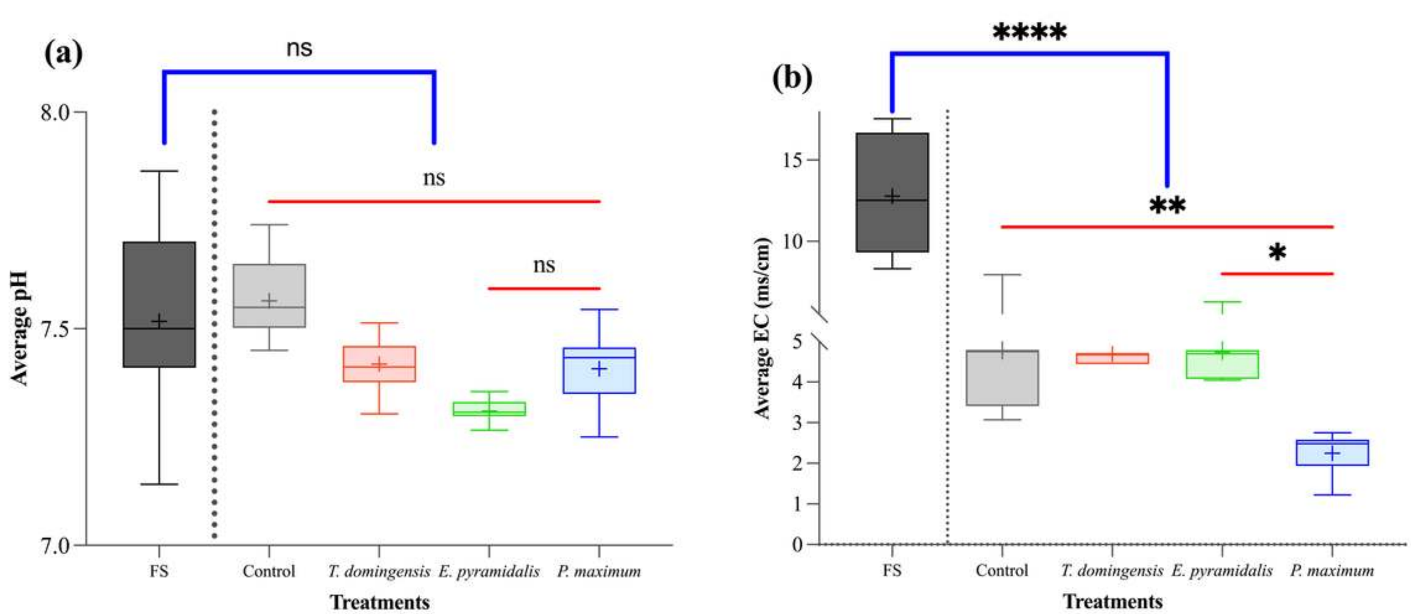

Figure 10

Comparison between the inlet and outlet of the STRBs of (a) pH values and (b) conductivity values

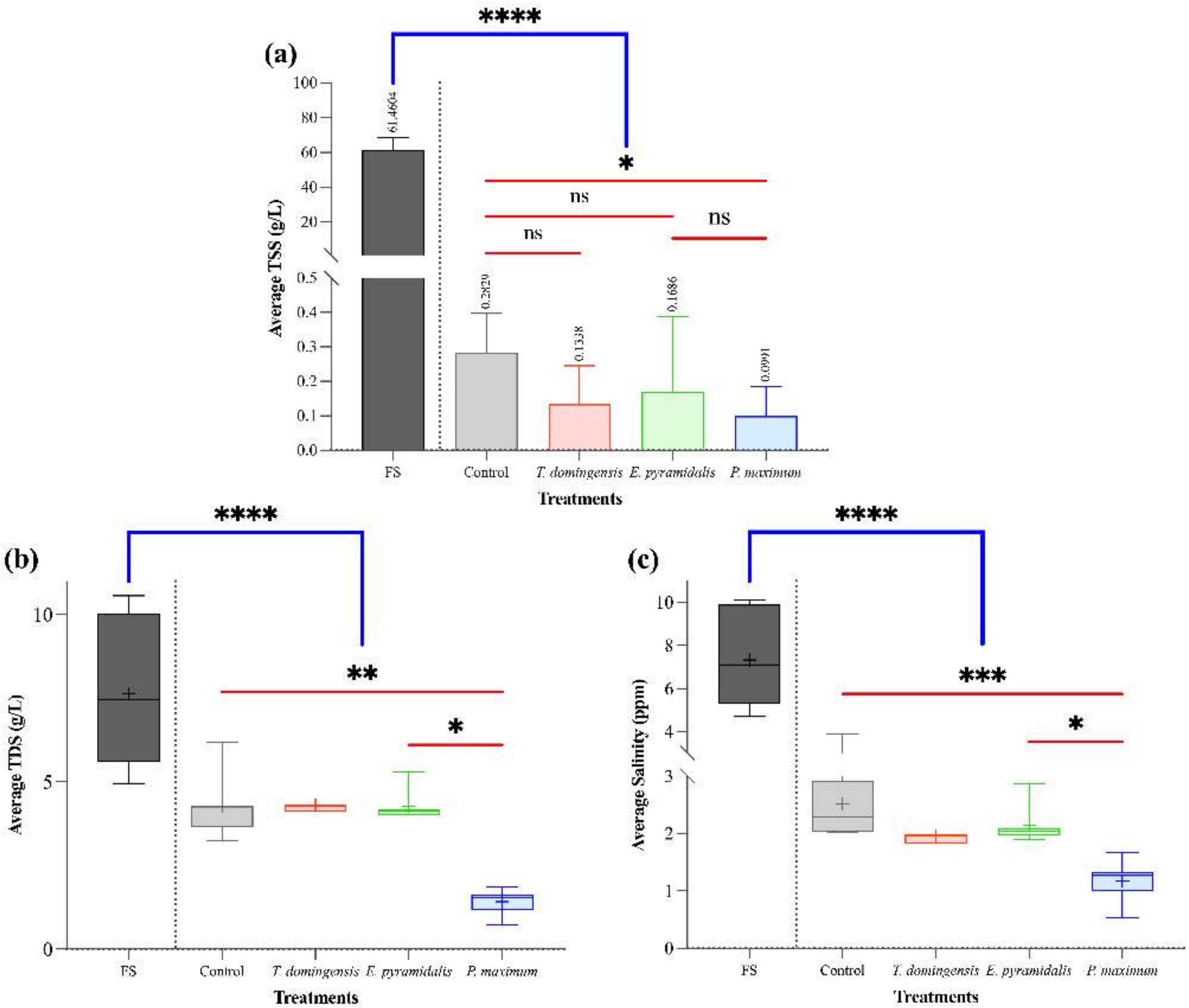

Figure 11

Removal of (a) TSS, (b) TDS, (c) Salinity

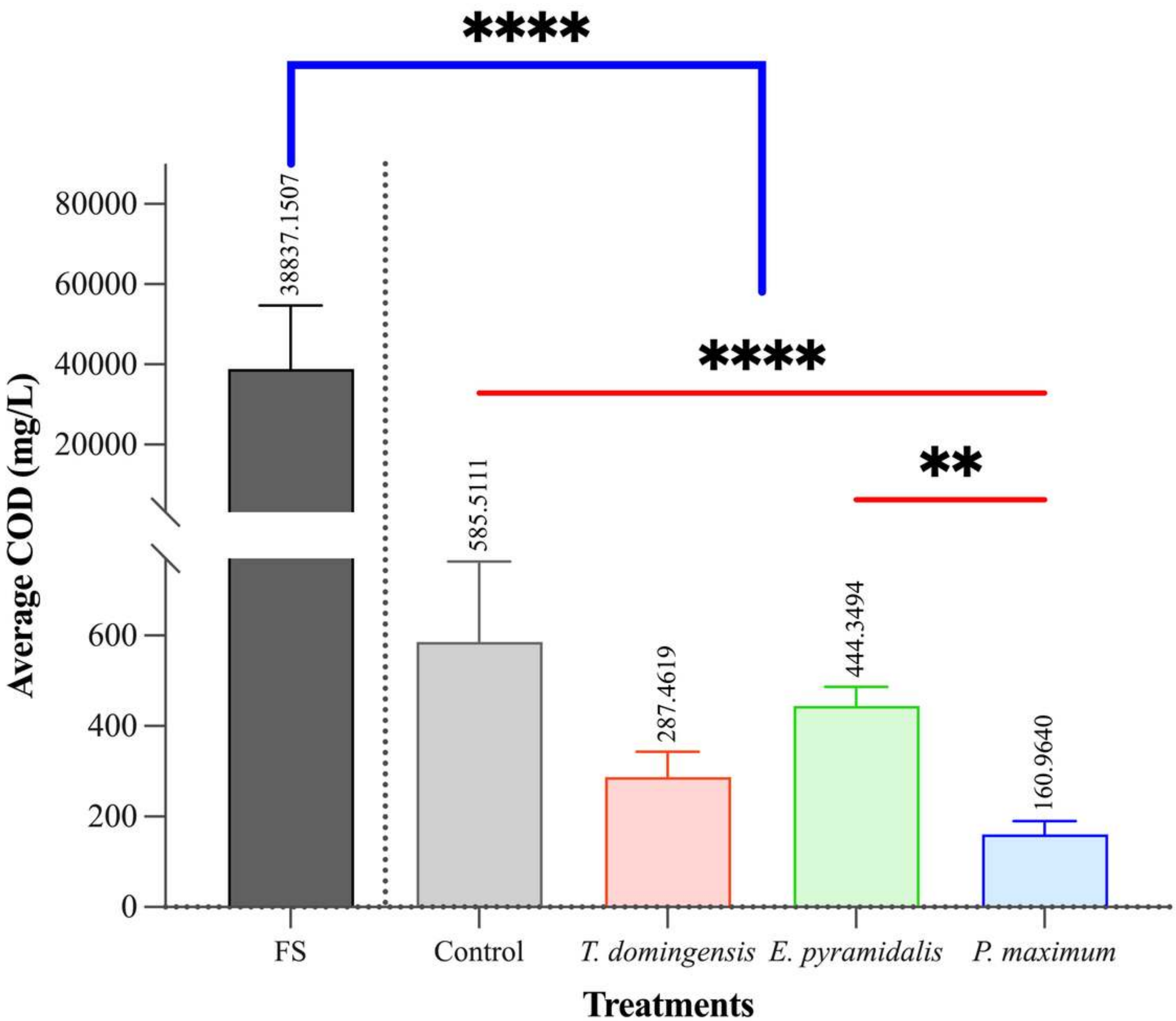

Figure 12

Removal of COD

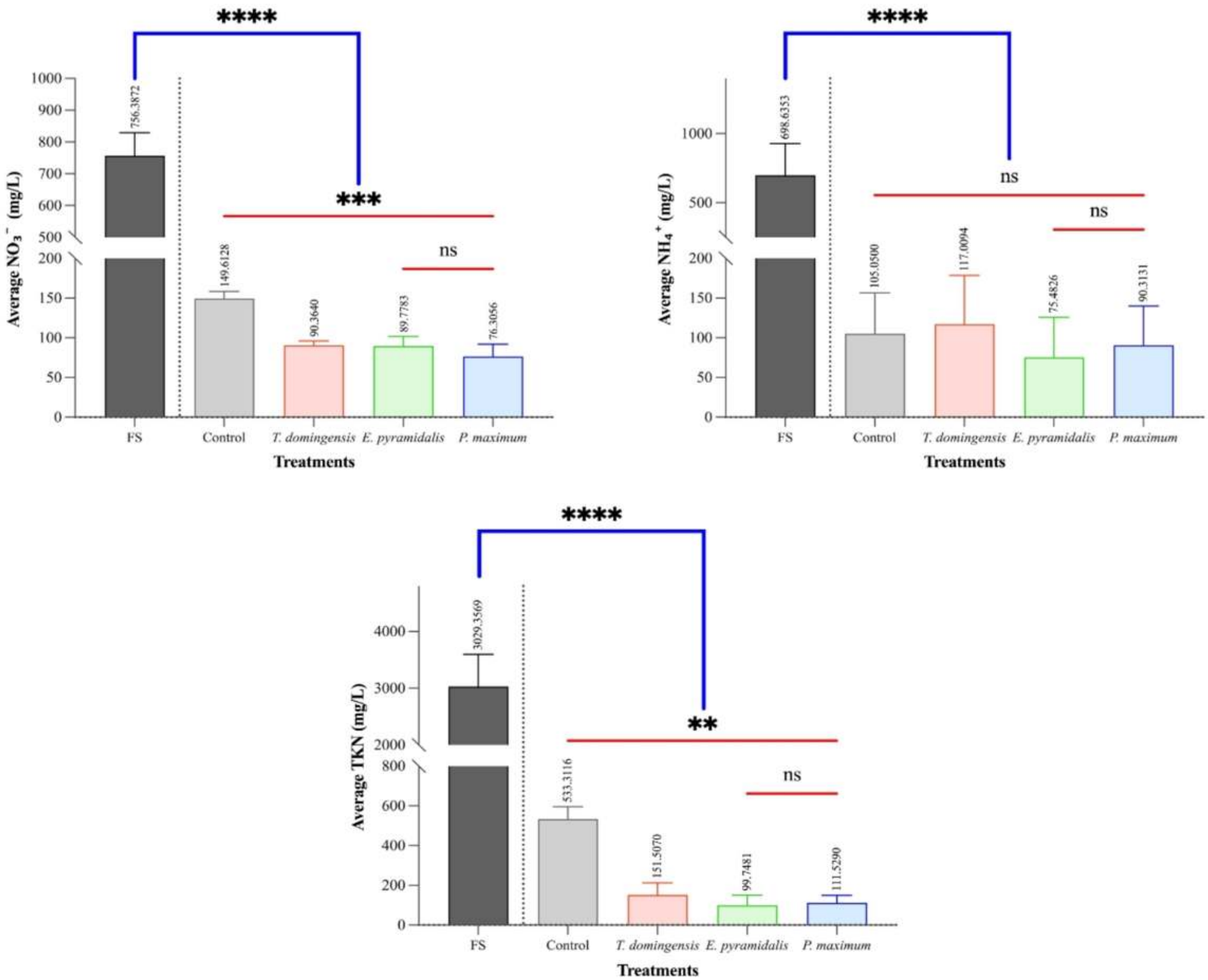

Figure 13

Removal of nitrogen

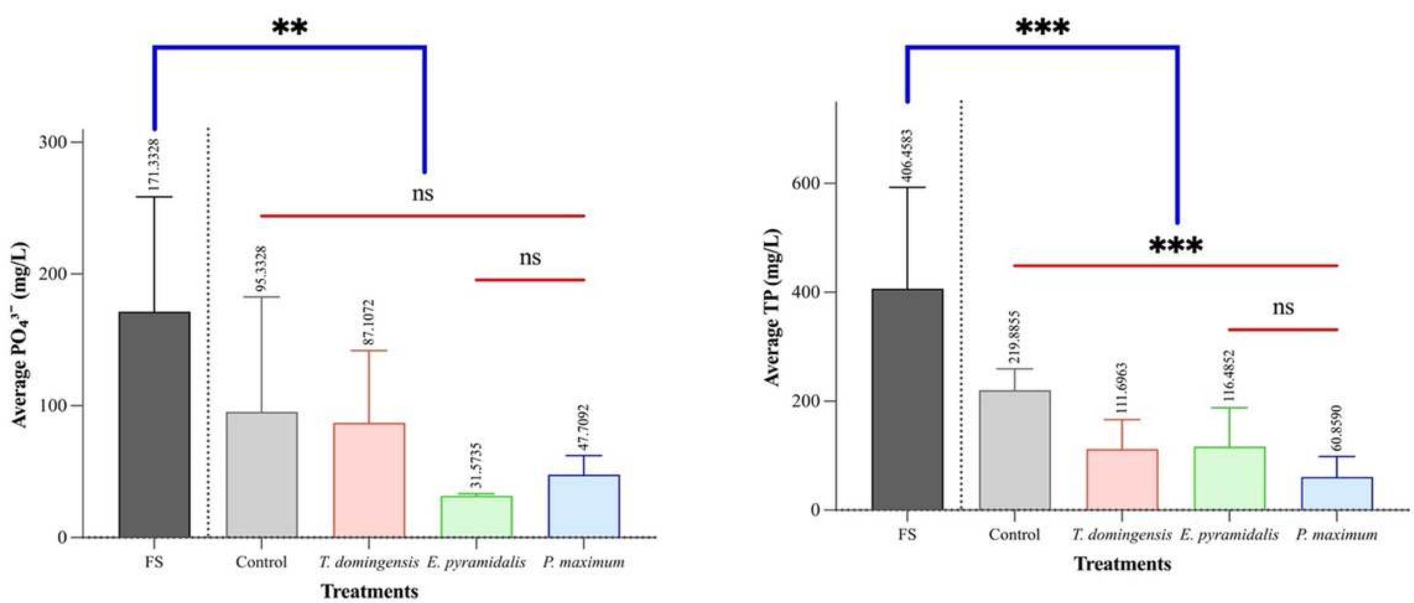

Figure 14

Removal of phosphorus

Supplementary Files

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