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Evaluation of the efficiency of Dracaena sanderiana in removing nutrients from synthetic wastewater by phytoremediation technology

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Abstract

The removal of nutrients from industrial wastewater is needed in order to mitigate water pollution. Phytoremediation is economical and environmentally friendly but there is limited research on the efficiency of Dracaena sanderiana for removal of phosphate and nitrate. The efficiency of the ornamental plant Dracaena sanderiana in removing nutrients and organic matter from synthetic wastewater in a hydroponic treatment system was evaluated in this study. Experiments were conducted for five days under controlled laboratory conditions and three runs were performed with different initial concentrations of pollutants to assess the effect of pollutant loading on the removal of phosphate, nitrate and chemical oxygen demand (COD). The first experiment showed 71–76% removal of phosphate, 71–73% removal of nitrate and about 57% removal of COD. In the second experiment, removal was 52–59% for phosphate, 65–69% for nitrate, and approximately 51% for COD. In the third experiment, the efficiencies declined to approximately 40% for phosphate, 51% for nitrate, and 49% for COD. The relative removal efficiency decreased as the initial pollutant concentration increased, likely owing to higher pollutant loading and saturation of the plant's absorption capacity. These findings indicate that Dracaena sanderiana is a feasible, low-cost, and eco-friendly option for improving water quality within a relatively short treatment period.

1. Introduction

Water is a fundamental natural resource that is essential for agricultural production, industrialization and human survival. It covers approximately 71% of the Earth's surface and is generally defined as a clear, odorless, and colorless substance. Water also underpins biological environmental and economic systems which makes its proper management a priority.

Nevertheless today's water resources face enormous challenges, including severe scarcity excessive pollution and overexploitation [1]. Strong conservation measures are therefore needed to ensure water security for present and future generations through sustainable management practices water conservation initiatives and the enforcement of stringent anti-pollution legislation [2].

Industrial wastewater consists primarily of two types of waste: sanitary waste and process waste. Sanitary waste originates from human activities such as the use of toilets and sinks whereas process waste is generated during the various stages of production and includes effluents from equipment and from heating and cooling operations. These operations frequently produce contaminated effluent and the presence of both organic and inorganic materials in the wastewater is responsible for the high levels of dissolved solids and biochemical oxygen demand (BOD) that are commonly observed [3],[4].

Many industries including leather tanning glass manufacturing sugar refining pulp and paper production electroplating textiles and mining require large quantities of water and are therefore characterized by very high water consumption [5],[6]. The wastewater they discharge contains a wide variety of pollutants that become mixed together during manufacturing [7]. These pollutants adversely affect aquatic systems and disrupt their natural processes eventually leading to their degradation [8]. Among them; phosphorus and nitrogen are particularly hazardous in water bodies because they trigger eutrophication which affects species both above and below the water surface [9].

Nitrogen and phosphorus contamination from urban and industrial wastewater is one of the most serious environmental problems especially in developing nations [10],[11]. Conventional water and wastewater treatment techniques such as chemical coagulation, rapid sand filtration, activated sludge processes and chlorination have helped protect human health and environmental quality over the past century. However, these methods often provide only limited nitrogen removal so more effective nutrient removal is still required.

Centralized treatment systems also have important drawbacks as they consume large amounts of energy and chemicals. They typically involve high capital and operating costs and have a large carbon footprint owing to their high energy demand. In addition they rely on chemical inputs and generate large quantities of sludge that require further treatment and disposal [12]-[13].

Phytoremediation encompasses several processes including rhizofiltration and phytoextraction. Rhizofiltration removes pollutants from aqueous solutions through adsorption and absorption by plant roots whereas phytoextraction mainly involves the uptake and accumulation of heavy metals in plant tissues. In the present study Dracaena sanderiana was selected as the candidate aquatic plant for phytoremediation because of its high nutrient uptake capacity and its usefulness in decontaminating wastewater [14].

Phytoremediation is among the most promising and environmentally beneficial techniques for managing and cleaning contaminated soil, water, and air [15]. Although Dracaena sanderiana (lucky bamboo) has been widely used to remove minerals from contaminated water, few quantitative studies have examined its performance under systematic variations in the concentrations of key nutrients under controlled laboratory conditions. Most previous studies focused on final removal rates without analyzing daily concentration changes or linking them to plant growth indicators such as height variation. By assessing nutrient removal efficiency at different concentration levels the present work directly addresses this gap and evaluates the system's potential for sustainable environmental applications.

Synthetic wastewater was used in this investigation because the concentration and nutrient content of the simulated water could be precisely determined and controlled throughout the experiments. This allowed an accurate evaluation of the ability of Dracaena sanderiana to absorb the target nutrients without interference from other pollutants that are often present in real wastewater. Because the experiments were conducted under controlled laboratory conditions, the observed treatment performance was closely linked to the selected pollutants. Although real wastewater contains additional and more complex constituents the results demonstrate the potential of this technique for practical application; further studies using actual wastewater are therefore recommended to confirm its effectiveness under real-world conditions.

2. Materials and methods

2.1 Experiment setup

A laboratory scale experimental system was designed and constructed to evaluate the efficiency of Dracaena sanderiana (lucky bamboo) in removing nutrients from artificially simulated wastewater. The system consisted of a transparent glass tank (wall thickness 10 mm) with dimensions of 50 cm × 15 cm × 50 cm (length × width × height) as shown in Fig. 1. The tank was filled with 35 L of synthetic wastewater prepared from tap water as the primary medium, in which the selected nutrient salts were dissolved under static non aerated conditions.

Fifteen healthy lucky bamboo plants with an average initial height of about 50 cm were used. Before the experiment the plants were acclimatized under laboratory conditions for 72 hours to ensure adaptation to the new environment and they were then distributed evenly over the water surface.

The synthetic wastewater was prepared by dissolving measured amounts of sucrose, urea and monoammonium phosphate in tap water to simulate the organic load and the nitrate (NO_3^-) and phosphate (PO_4^{3-}) content of real wastewater respectively.

Samples were collected from three depths (20, 30 and 40 cm from the bottom of the tank) to evaluate pollutant removal within the root zone influenced by the plant system these depths were selected to cover the full vertical extent of the Dracaena sanderiana root zone.

The experiment was conducted under natural light within a controlled temperature range of 20–25 °C. Water samples (250 mL from each depth) were collected daily for five consecutive days and were stored at 4 °C prior to analysis to preserve their chemical stability.

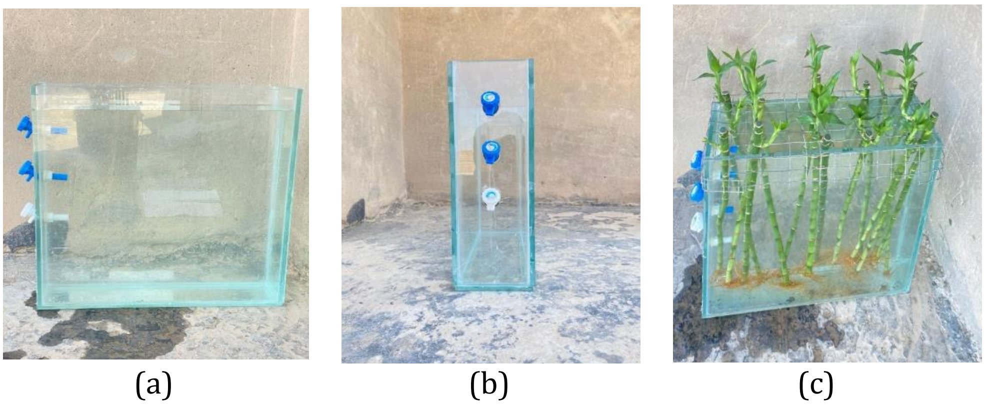
(a) (b) (c)

Fig. 1. The experimental design of the Dracaena sanderiana processing system: (a) side view without plants; (b) frontal section showing the sampling method; and (c) side section showing the distribution of plants inside the tank.

2.2 Steps of the experimental work

The first step was the preparation of the treatment system. The plants, purchased from a local nursery were carefully rinsed with tap water before being placed in the treatment tank to remove any residual impurities.

Synthetic wastewater was prepared in the laboratory by dissolving measured amounts of sucrose urea and monoammonium phosphate in tap water to approximate the organic load and the nitrate and phosphate content respectively using a 35 Liter treatment tank. Under identical operating conditions three separate experiments were carried out with different initial pollutant concentrations. After the wastewater was prepared the aquatic plants were placed in the tank and allowed to acclimatize for 72 hours before sampling began. Following this acclimatization period, water samples were collected every 24 hours for five days. To assess treatment performance across the entire water column one sample was collected daily from each of the three selected depths (20, 30, and 40 cm from the bottom of the tank). Chemical oxygen demand (COD) , nitrate (NO_3^-) , phosphate (PO_4^{3-}), pH, and total dissolved solids (TDS) were measured in the collected samples. The initial concentrations of the main pollutants were also measured immediately after preparation and served as the basis for evaluating removal efficiency. In accordance with standard sample handling procedures, the samples were kept in clean opaque containers at 4 °C and were analyzed within 24 hours of collection without the addition of any chemical preservatives.

The system was exposed to natural light for (10–12) hours per day and the water temperature was maintained at (20–25) °C to provide stable operating conditions. Daily observations of the external appearance of the plants including visible growth, leaf color, and root condition were recorded. The water level in the tank was also monitored daily to account for evaporation losses and to confirm that changes in pollutant concentrations resulted from the biological treatment process rather than from external factors.

2.3 Methods of analysis

Water samples were collected daily from the treatment tank for nutrient analysis to verify the nutrient removal efficiency of Dracaena sanderiana using the standard methods described in APHA (2017) [16]. Table 1 lists the parameters tested, the analytical methods and the instruments used.

Table 1. Types of tests analytical methods and devices used.

Types of tests	Work method	The device used
Total dissolved solids (TDS)	2510 B (Conductivity method)	The OAKTON® pH/conductivity/°C/°F/TDS meter
pH	4500-H+ PH VALUE	The OAKTON® pH/conductivity/°C/°F/TDS meter
phosphate (PO_4)	4500-P E. Ascorbic Acid Method	phosphate meter (HANNA HR Phosphate Meter, H1717-25, Romania
nitrate (NO_3)	4500-NO_3- B	UV-Visible spectrophotometer UVD3000 (LABOMED, USA)
chemical oxygen demand (COD)	5220 D. Closed Reflux Method	HACH® closed reflux colorimetric COD analyzer, Germany

TDS and pH were measured using an OAKTON pH/conductivity/TDS meter. Phosphate (PO_4^{3-}) was determined by the ascorbic acid method and nitrate (NO_3^-) was measured using a UVD3000 UV–visible spectrophotometer at a wavelength of 220 nm. COD was analyzed by the closed reflux method using a HACH colorimetric COD analyzer by mixing 3.5 mL of sulfuric acid, 1.5 mL of potassium dichromate reagent and 2.5 mL of sample according to the standard procedure.

2.4 Water quality and phytoremediation system characterization

The synthetic wastewater used in this study was prepared in the laboratory to mimic nutrient polluted water under carefully controlled conditions (temperature 20–25 °C) (natural light 10–12 h per day); five days of operation). Samples were collected every 24 hours and each experiment was performed in triplicate. To ensure the stability and repeatability of the experimental setup, the initial concentrations of the main pollutants were measured prior to the start of each experiment. Because nutrient-related parameters (nitrate, phosphate and COD) are among the most important indicators for evaluating phytoremediation performance, they were used as the key water-quality indicators in this study, together with pH and TDS. The initial physical and chemical characteristics of the synthetic wastewater, measured before treatment, are presented in Table 2.

Table 2. Initial Characteristics of synthetic wastewater.

Component	Concentration experiment 1	Concentration experiment 2	Concentration experiment 3
COD, mg/L	260	410	540
NO_3, mg/L	37.99	43.36	49.13
PO_4, mg/L	13.4	26.9	37
PH	5	5	6
TDS mg/L	650	750	811

2.5 Calculation of pollutant removal efficiency

The pollutant removal efficiency was calculated using Eq. (1) to compare pollutant concentrations before and after treatment over equal operating periods:

$$Removal\ Efficiency\ (\%) = (C0 - Ct)/C0 \times 100 \tag{1}$$

where C_0 is the initial concentration (mg/L) and C_t is the concentration at time t (mg/L).

This equation was applied to calculate the removal efficiencies of COD, nitrate and phosphate in each experiment under identical operating conditions (temperature, light period, residence time and plant density). Only the initial pollutant concentrations were varied between experiments to represent different pollution loads based on data from previous studies and to evaluate system performance under low, medium, and high pollution conditions.

3. Results and discussion

3.1 Chemical Oxygen Demand (COD) removal efficiency

Fig. 2 shows a clear direct relationship between hydraulic retention time (HRT) and (COD) removal efficiency with the efficiency increasing gradually over time. A noticeable increase occurred between the first and third days indicating that the biological activity of the system intensified during this period. In each experiment the highest removal rate was achieved on the fifth day showing that longer contact between the contaminated water and the plant system led to better performance. The three curves display a rapid increase in COD removal efficiency during the initial stages of treatment followed by a gradual decline in the rate of increase as the system approached a plateau, indicating saturation-based removal behavior. The effect of the initial pollutant concentration is reflected in the variation between experiments. The removal efficiency obtained in this study ranged from 49% to 57% within a 5-day HRT whereas a previous study [17]. reported a removal efficiency of 66.5% after 42 days. Although the efficiency here was slightly lower, the much shorter HRT indicates the potential of the applied plant system for rapid wastewater treatment. These findings are further supported by [18], which confirmed the effectiveness of aquatic plants in improving wastewater quality.

In the first experiment (Fig. 2) the COD removal efficiency rose to 57% by the fifth day, the highest among the three experiments. This gradual increase suggests that the plant system enhances the biodegradation of organic matter at longer HRTs, as the moderate organic loading favored microbial activity. The greater stability of such systems at moderate organic loads is consistent with the high efficiency observed under low loading. In the second experiment (Fig.

2) the COD removal efficiency reached 51% by the fifth day with a relatively rapid increase between the first and third days. The moderate concentration provided a sufficient supply of organic carbon, which enhanced microbial activity and explains this rapid improvement. Although bacterial biomass growth in the rhizosphere is generally promoted by a moderate organic load, the higher load in this experiment produced a lower final efficiency than in the first experiment.

In the third experiment (Fig. 2), the system showed the lowest final removal efficiency, reaching 49% on the fifth day. This was attributed to the higher organic load resulting from the doubled initial concentration the decrease in dissolved oxygen consumed during the oxidation of organic matter and possible plant stress. Under these conditions, the system shifted toward reducing conditions, which lowered the COD removal efficiency.

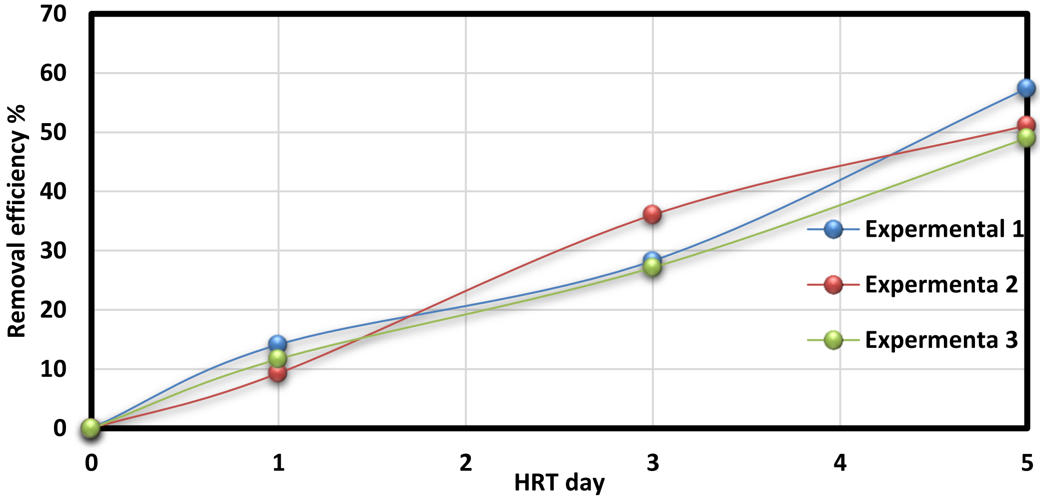

Fig. 2. COD removal efficiency in the three experiments over the operating period.

3.2 Phosphate (PO4) removal efficiency

Fig. 3 shows the variation in phosphate removal efficiency with HRT at different sampling depths (20, 30 and 40 cm) in the first experiment. At the start of operation (day 1) the low removal efficiency (10–15%) reflects an immature system in which biofilm development, root–microbe symbiosis and mass transfer processes had not yet reached steady state. At this stage, phosphate transport toward the root zone was primarily diffusion limited and the weak concentration gradients (∇C) resulted in reduced nutrient flux in accordance with Fick's law.

As the HRT increased, the removal efficiency rose gradually to 25–35% on the second day and 40–50% on the third day. This improvement is attributed to the gradual development of a stable root system within the tank characterized by stronger diffusion gradients at the water root interface, an increase in phosphorus-absorbing microbial biomass and improved biofilm formation on the root surfaces. The oxygen released from the roots simultaneously created local aerobic zones that boosted microbial metabolism and promoted phosphorus transformation. Together, these processes greatly increased phosphorus flux toward the biological absorption sites. In the final phase (days 4–5), the system reached quasi-steady conditions and achieved its maximum phosphate removal efficiency, ranging from 65% to 76% depending on the sampling depth.

This performance was supported by the fully developed root structure, the higher root surface-area density and the longer HRT, all of which improved mass-transfer efficiency. Rather than being governed by a single mechanism, phosphate removal was controlled by several interconnected pathways including direct phosphorus uptake by plants for metabolic and structural functions; incorporation of phosphate into microbial biomass within biofilms, adsorption onto the root surfaces and the supporting medium and precipitation of insoluble phosphate compounds, which is influenced by local pH variations particularly in microenvironments with strong reducing conditions. This indicates that phosphorus removal was governed by interconnected biogeochemical processes within the treatment tank rather than by simple physical absorption. Compared with previous research on constructed-wetland systems, the removal efficiencies (65–76%) fall within the reported range for mature systems; differences in HRT, plant species, root-density development, oxygen-transfer efficiency, and biofilm maturation can explain the variation between studies [19], [20],[21].

Fig. 4 illustrates the variation in phosphate removal efficiency with HRT in the second experiment at the same sampling depths. The efficiency increased gradually from 16–19% on the first day to about 30–36% on the second day and 45–48% on the third day reaching approximately 52–59% by the fourth and fifth days. In addition to the plants capacity to absorb and store nutrients in their tissues, this increase is attributed to the growth of root-associated microbial biomass which plays a crucial role in the transformation and removal of phosphorus [21].

Fig. 5 shows the variation in phosphate removal efficiency with HRT in the third experiment. The efficiency again increased gradually over time but remained lower than in the previous two experiments, rising from about 19% at the start to 27% on the second day, 33–36% on the third and fourth days, and almost 40% on the fifth day. This lower performance is explained by the higher nutrient load, which saturates the absorption sites of the plant and the supporting medium and thereby reduces the relative removal efficiency; nevertheless, the system continued to remove a portion of the phosphate through plant uptake and microbial transformation in the root zone. The results also suggest that the sampling depth influences phosphate removal by affecting the contact time among the water, the plants, and the supporting medium.

Finally, phosphate removal was strongly associated with the simultaneous removal of COD and nitrogen. The increased microbial degradation of organic matter raised the activity of the microbial biomass in the root zone, which improved phosphorus uptake a vital nutrient for microbial growth while a balanced supply of nitrogen and phosphorus enhanced nutrient uptake by both plants and microbes. This indicates that phosphate removal was part of an integrated biological treatment mechanism governed by microbial activity and nutrient balance rather than an independent process.

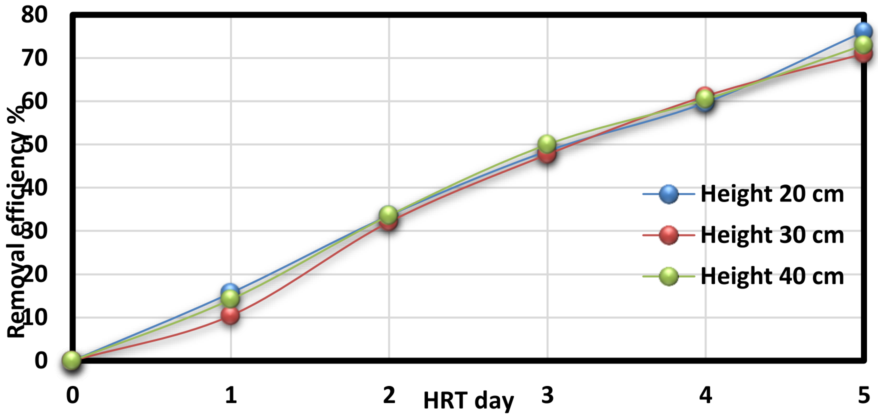

Fig. 3. Phosphate removal efficiency over five days at different sample heights (experiment 1).

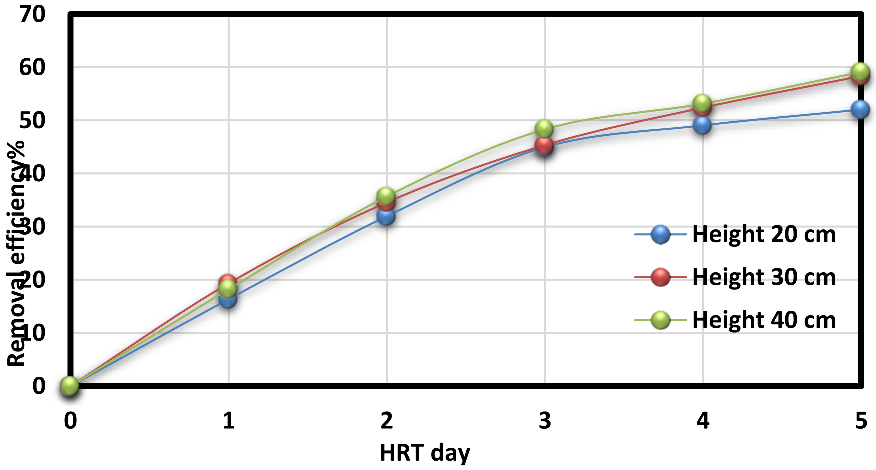

Fig. 4. Phosphate removal efficiency over five days at different sample heights (experiment 2).

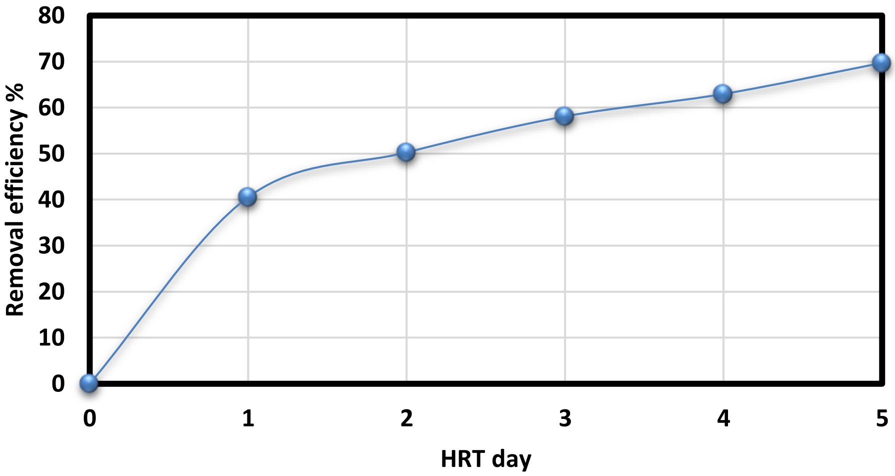

Fig. 5. Phosphate removal efficiency over five days at a height of 30 cm (experiment 3).

3.3 Nitrate removal efficiency

Fig. 6 shows the change in nitrate removal efficiency in the first experiment (low initial concentration) as a function of HRT. The efficiency rose progressively with HRT increasing from roughly 32–39% on the first day to about 70–73% by the fifth day at the different sampling depths (20, 30, and 40 cm). This improvement can be attributed to the microbial nitrogen transformations occurring in the root zone and to nitrate uptake by Dracaena sanderiana as part of its nutrient assimilation. Aerobic conditions near the root surfaces promote nitrification whereas oxygen limited zones in the system support denitrification which together enhance nitrate removal [22].

Fig. 7 shows the results of the second experiment (moderate initial concentration), which exhibited a gradual improvement in nitrate removal efficiency with HRT. By the end of the treatment period the efficiency had increased from about 24–30% on the first day to about 65–70%. The efficiency also improved markedly with the depth of the water layers with the highest values recorded at a depth of 40 cm. This can be linked to the oxygen distribution in the tank where aerobic zones near the roots and the relatively anaerobic deeper layers enhance nitrification and denitrification and thus improve biological nitrate removal [22].

Fig. 8 shows the results of the third experiment conducted at a single depth with a high initial nitrate concentration. The efficiency increased gradually from about 27% on the first day to about 51–52% on the fifth day. Compared with the first and second experiments, the removal efficiency was lower. This poorer performance may be due to nitrate overload, which can stress the microbial communities and limit oxygen in the system, reducing the efficiency of nitrification and denitrification [23].

Overall, the findings show that plant uptake, microbial activity, HRT and oxygen distribution within the treatment tank interact to determine the nitrate removal efficiency of this Dracaena sanderiana system. While the plants assimilated nitrate into their tissues, microbial processes particularly nitrification and denitrification played an important role in improving the overall nitrate removal efficiency [24].

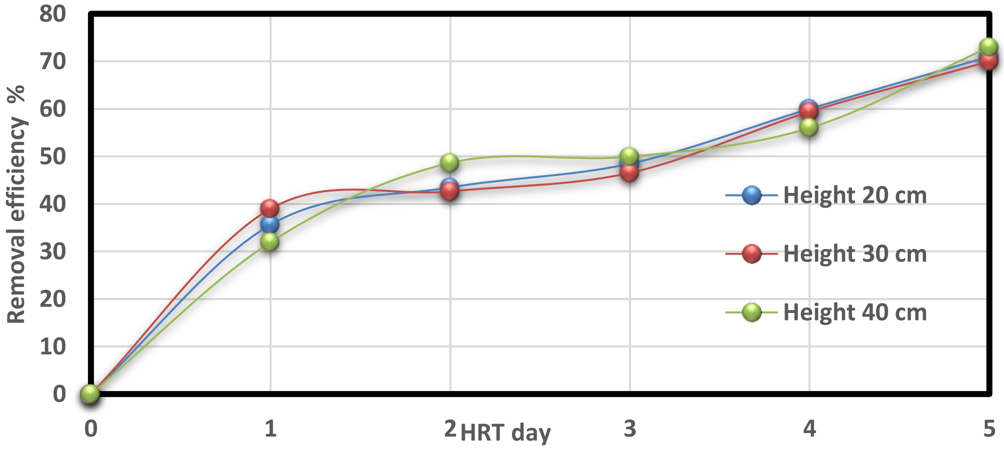

Fig. 6. Nitrate removal efficiency over time for the first experiment at different heights.

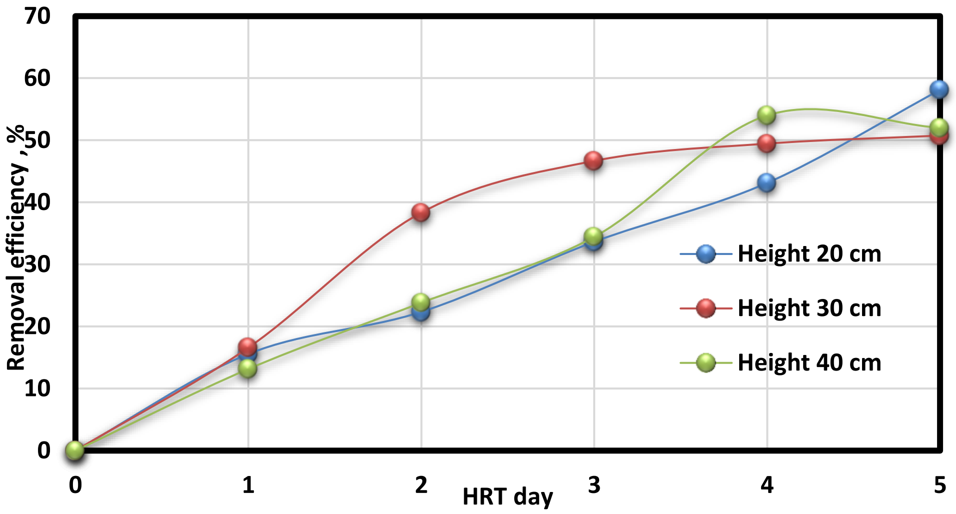

Fig. 7. Nitrate removal efficiency over time for the second experiment at different heights.

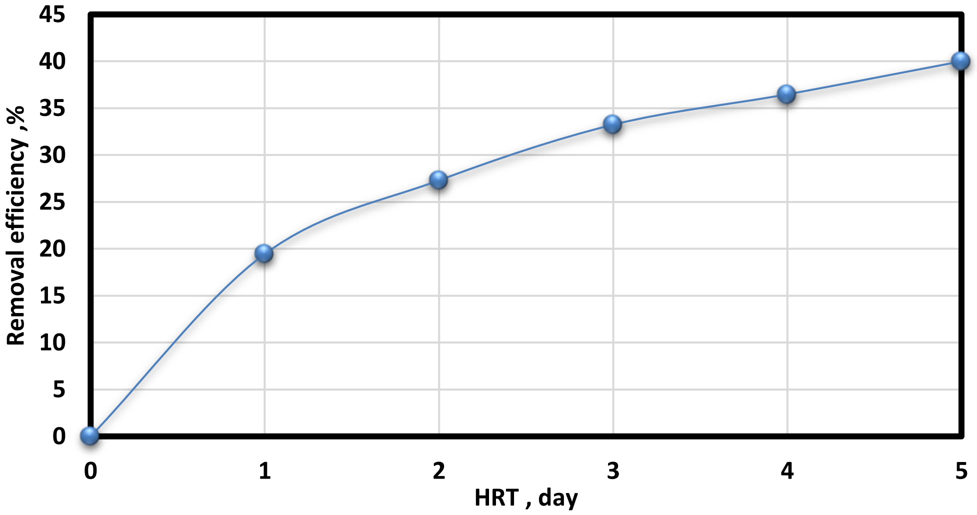

Fig. 8. Nitrate removal efficiency over time for the third experiment at a height of 30 cm from the bottom.

4. Conclusions

This study evaluated the efficiency of Dracaena sanderiana in removing nutrients and organic matter from synthetic wastewater using a batch hydroponic system operated for five days. The results showed that the phytoremediation system effectively reduced the concentrations of phosphate, nitrate and COD in the water. Removal efficiency was highest in the first experiment and decreased progressively as the initial pollutant concentration increased indicating that higher loading stresses the system. At elevated concentrations, oxygen limitation, microbial inhibition and mass-transfer constraints among the pollutants, plant roots and microorganisms reduced the overall treatment performance. Pollutant removal was governed by a series of interrelated processes, including nutrient uptake by the plant, adsorption within the system and microbial activity in the root zone. From a practical standpoint, the system was simple to operate, required no complex equipment or high energy input and was relatively low cost compared with conventional treatment methods. Achieving substantial removal within a short five-day period highlights the potential of this approach as an effective and environmentally friendly method for treating nutrient-polluted water and improving water quality.

5. Recommendations

1. Evaluate the system's performance using real wastewater to assess its efficiency under practical conditions.
2. Analyze the effects of operational conditions such as dissolved oxygen, temperature and lighting on removal efficiency.
3. Investigate the pollutant removal mechanisms (plant uptake, microbial activity, nitrification, and denitrification) in greater depth.
4. Assess the long-term performance of the system to determine its stability and sustainability.
5. Evaluate the scalability of the system for practical, full scale application.

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