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Ensuring Sustainability via Application of Root Zone Technology in a Rubber Product Industry: A Circular Economy Approach

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Abstract: Rapid urbanization has led to the exploitation of water quality and quantity. Urban growth and its activities result in the pollution of freshwater by generating different types of waste. Root Zone Technology (RZT) has successfully been adopted and employed in several countries to promote sustainable development. RZT paves the way for the incorporation of automated dynamics into an artificial soil ecosystem. This study's primary goal was to develop a water treatment process for industrial effluents naturally and effectively using RZT. The technology adopts layers of coarse and fine aggregates, charcoal, sand, and planted filter beds consisting of compost media to treat effluents; the system is easily installed, low-maintenance, and has low operational costs. Selected plants achieved a result of 50–80% pollutant removal. RZT reduces the characteristics of effluents, such as chemical oxygen demand, biochemical oxygen demand, pH, color, TSS, TDS, BOD, COD, etc., by a more significant amount. Further studies of more plant species should be performed to improve this technology. Soil tests will also be an excellent option for understanding the concepts of reed absorption mechanisms. In addition, incorporating modeling in agricultural systems will be beneficial for future studies.

Keywords: wastewater treatment; Root Zone Technology (RZT); circular economy; sustainable environment

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1. Introduction

Increasing environmental pollution is a threat to all living organisms, including humans [1–3]. Despite the successful field applications of effluent treatment technologies, the management of industrial effluents is still a challenging task for scientists and researchers worldwide. Nowadays, ecologically friendly technologies are receiving worldwide attention, especially Root Zone Technology (RZT) [4]. 'Root Zone' is a scientific term that is used to cover all the biological activity among different types of microbes, the roots of plants, water soil, and the sun [5]. Thorat et al. [5], found that plants in the bed were initially acclimatized for two weeks with appropriate dilutions each time. The concentrations of sewage through plant treatment grew with time, reaching levels of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. Colocasia esculenta and Canna were used to treat these samples by phytoremediation.

The RZT was first reported to be a potential environmental solution by Seidel and Kickuth in 1952 [6]. By 1995, almost 200 units based on RZT had been constructed in Europe, including Denmark and Germany, and by then the USA had installed up to 200 units. However, there were notably fewer units in India than in these countries. However, up to 50–60 units were reached by 2005, and since then, more people, industries, and institutions have come up with successful applications for this technology.

RZT has been reported to mitigate various environmental problems, specifically those associated with aquatic environment contamination [7]. Various researchers have highlighted that industrial effluents are mostly discharged to surface water bodies (streams, rivers, etc.), notably without meeting the imposed discharge guidelines. Increasing water footprint requirements of current industries revealed that industries must take the lead on maximizing the reuse of treated effluents. As reported by Thorat and co-authors, RZT can be used for domestic as well as industrial effluent treatment [5]. The most successful plant so far tested for RZT is reeds. In addition, microorganisms and reed beds are integral to root zone technology. Therefore, this technology is sometimes known as reed bed or constructed wetland system as the water gets purified by the roots of the plants [8,9].

In RZT, the root zone process incorporates the self-regulating dynamics of an ecosystem and effectively purifies the domestic as well as industrial effluents. In general, we can say that the RZT is an easy-to-build, operate, and natural maintenance-free system in which the roots purify the wastewater fed to the plants used [10]. It is worth mentioning here that this technology does not need a long preparation time [11,12]. Various plant species e.g., alligator weeds, water hyacinths, Solms, mangroves, hydrilla, etc., grow by themselves in natural wetlands. Unlike other treatment technologies, no chemical addition is needed for RZT [4]. For such a treatment system, the screened effluents are usually fed after minimizing the suspended solids concentration.

The advantages and applications of RZT have already been discussed in various papers. One of the remarkable advantages of this technology is that it can achieve standards for tertiary treatment at a low cost as it does not need electricity or chemicals to meet the performance requirements and is also efficient in the irrigation process [13] with minimum monitoring requisition [14]. Besides, the sludge settlements are also evidently smaller, and the ambiance with greenery can become a habitat for birds [15]. Previous studies highlighted that the salt content of wastewater has no significant impact on the function of the reeds [16,17]. Furthermore, an impervious layer of soil is recommended when wastewater is fed via various pathways and/or directions [18]. In a few studies, a modeling approach is also applied for evaluating the growth of crops, the amount of water given or absorbed, water movement, nitrogen dynamics, and types of pesticides used for agriculture [19].

The circular economy (CE) describes the concept through which products and raw materials stay in the economy as long as possible, and where waste is treated as a secondary raw material that can be recycled and used again. Water management is an integral part of the economy because many industries rely on water for their basic requirements [3]. Production and profits will be limited if the water supply cannot meet demand. The CE is based on more sustainable management of raw materials (such as water) and waste since water (including wastewater) is of major concern in the current period [20]. The water and wastewater sectors can be linked to a circular economy when the existing tools, such as the CE model framework, are modified; this method is applied to the water and wastewater sector and is different from linear economy-based tools [20,21]. The "take–make–use–throw away" system is the highlight, focusing on waste, which is usually the last step in the lifecycle of a product [21,22]. CE is a concept that encourages the use of materials and energy by being environmentally friendly, as it reduces the amount of waste made and reuses it as secondary material [23]. The main reasons for implementing a circular economy globally are:

- Limited availability of raw materials and resources.
- The dependence on imported raw materials (i.e., high prices, volatile markets, and uncertain political situations in some countries).
- Decreasing competitiveness of the global economy.

Given this background, this study aimed to examine the treatment of industrial effluent using RZT in Periyamkulam pond in Coimbatore, in the state of Tamil Nadu, India. Rathinasamy et al. [24], prepared a tank setup and applied horizontal flow to analyze the treatment efficiency. This study attempts to determine an effective method to increase the treatment efficiency of plants by utilizing a low-cost technology, i.e., RZT. This study describes the RZT system, which planted filter beds consisting of soil gravel, sand, and fine aggregate.

2. Materials and Methods

Effluent from Alleppey Latex Pvt. Ltd. has been used for research purposes, which is a manufacturing company that produces rubber-based products. For this RZT, water collection is performed by the same manufacturing company. It is collected from the collection tank, where effluent water is stored at the end of the process (Figure 1). This effluent water has been used for latex industrial processes, centrifuge, machine, and floor washing. All the effluent is collected in a storage tank. The water sample analysis was conducted at different stages. Water was collected at regular intervals for the study of the physicochemical characteristics (Figure 2). Accordingly, the following analysis has been performed.

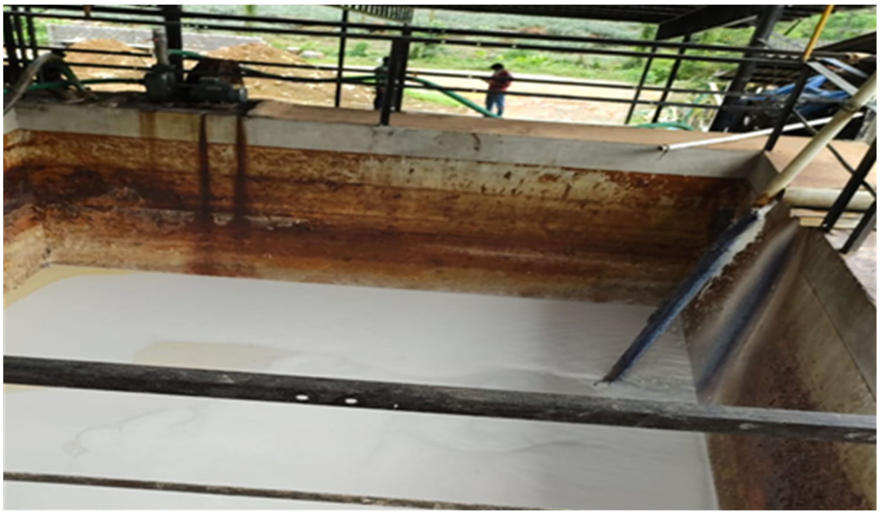

Figure 1. Sample collection area.

Figure 2. A water sample collection from the study area.

Steps of Construction and Procedure of RZT

The construction of wetland has been performed with considering a size of 35 cm × 55 cm × 45 cm for both vetiver and colocasia plants (Figure 3). Consider the reactor thickness to be 45 cm, length to be 52 cm, and height 35 cm. Initially, 5 layers are identified and water is drained out by tubes placed at the bottom. This is performed first. Tubes can also be placed initially at the bottom to take the water out.

Figure 3. Steps of construction; (**a**) colocasia and vetiver while planted initially for normal watering, and (**b**) growth of colocasia and vetiver after normal watering.

The reactor system must be filled with washed aggregate up to 10 cm thick at the bottom to construct the wetland system, then filled with charcoal at the second layer up to 10 cm (Figure 4). The third layer of river sand is up to 10 cm at the next layer and another layer of ordinary sand. The topsoil is filled up to 20 cm, and as the growth progresses, compost media that consists of cow dung, leaves, etc. The root zone method passes through several stages. Sample collection from the industry is the initial stage, and later the unit or reactor is constructed by placing separate layers of gravel and charcoal sand, which includes river sand and the sand used for farming; after arrangement into different layers, the plants will be planted in the unit. Gravel can precipitate containing impurities. Various sand and related sand filters are used widely in effluent water treatments. Charcoal removes toxins from water, especially volatile organic compounds and chlorine harmful to groundwater (Figure 5).

Further, the growth of plants is monitored each day. Reed plants can grow in a faster manner; they grow from 3 cm to 5 cm within a few days and can reach up to 12 cm to 15 cm in 1.5 months. Further, the constructed wetland size of 55 cm × 35 cm × 45 cm has been considered. The length of the reactor is 55 cm, the height is 35 cm, and the thickness is 45 cm.

Figure 4. Experimental setup after completion.

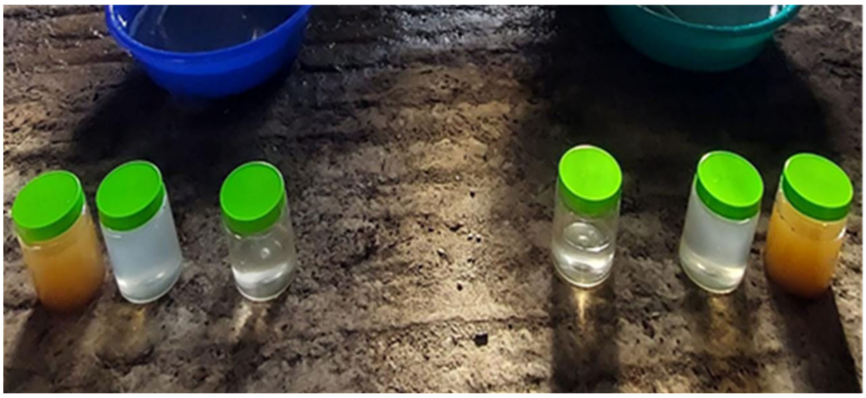

Figure 5. Treated water was collected after 5, 10, and 15 days.

During the growth period of 2 months, plain or tap water should be sprinkled for plant growth. The wastewater will be fed into the root zone system, and treated water is collected. A sample has been taken for analysis. The roots of the reed make a pathway for the water to move freely and oxygen from the roots embedded in the soil, causing aerobic conditions for bacterial growth. These processes cause the breakdown of ammonia into nitrates by oxidation. These organisms are necessary to break down many compounds in the oxidation of ammonia to nitrate. This is the first step in the biological breakdown of nitro compounds. This process is called nitrification; the plants themselves take up a certain amount of nutrients from the wastewater [25]. The proper standard for water quality is gained with the aid of the reed beds, as they remove bacterial and viral contaminates and reduce the BOD, TSS, and nitrogen concentrations. The filter bed material, wetland plants, and microorganisms react with the wastewater and influence the mineralization process of the biodegradable materials in the soil matrix. The classification of this process is purely based on the physical, chemical, and biological characteristics, followed by the normal watering plants further grown with the effluents. The treated effluents are tested at regular intervals.

3. Results and Discussion

Sample analyses were conducted as per Central Pollution Control Board, India guidelines (BIS: 3025) [26] at each stage of treatment and the treated water was analyzed at regular intervals. The analyzed characteristics included pH, TSS, TDS, turbidity, TN, COD, BOD, and color. The industry's raw wastewater has a pH of 3.4, 2200 mg/L TDS, 1100 mg/L TSS, 120 mg/L TN, 40 NTU turbidity, 3500 mg/L BOD, and 7000 mg/L COD. Further, during treatment, the efficiency of the applied plants was calculated from the collected performance data. The pollutant reduction efficiency, along with overall treatment efficiency, was also reported in this study. Table 1 represents the analyzed characteristics of both plants in RZT.

Table 1. Comparison of colocasia and vetiver plants in terms of effluent characteristics.

Parameter Analyzed	Detention Time (d)	*Colocasia* Plants	*Vetiver* Plants	Desirable Limit
pH	5	4.5	5	6–8
	10	5.4	5.8	
	15	6.1	7.2	
TDS (mg/L)	5	1790	1750	2100
	10	960	950	
	15	630	620	
TSS (mg/L)	5	1070	1050	100
	10	850	837	
	15	786	765	
TN (mg/L)	5	96	83	50
	10	53	45	
	15	38	36	
Turbidity (NTU)	5	23.5	21	1–5
	10	15	14.8	
	15	12.2	8.5	
BOD (mg/L)	5	3000	3020	30–100
	10	1950	1932	
	15	920	910	
COD (mg/L)	5	6985	6875	250
	10	4525	4498	
	15	2655	2640	

3.1. Changes Observed in Characteristics of Colocasia and Vetiver Plants in Root Zone Technology

The experiments revealed that the pH of the *colocasia* plant after 15 days was 6.1, and for *vetiver* it was observed as 7.2 (Table 1). Regarding TDS reduction, the *colocasia* plant resulted in slightly higher TDS values (630 mg/L) when compared with the *vetiver* plant, after 15 days. Regarding TSS, the *colocasia* plant resulted in TSS of 786 and for the *vetiver* plant, TSS was 765 mg/L. The TN value of the *colocasia* plant was determined as 38 mg/L, which was almost similar to the values obtained with the *vetiver* plant. The turbidity values of effluent with plant after 15 days were noted as 12.2 NTU and 8.5 NTU for *colocasia* and *vetiver*, respectively. In addition to the parameters mentioned earlier, BOD and COD were also considered in the study to assess the performance of both plant-based systems. The value of BOD observed for the *colocasia* plant was 920 after 15 days, which was slightly higher than the values obtained for the *vetiver* plant. The COD value for the *colocasia* plant after 15 days was observed as 2655, whereas that for the *vetiver* plant was observed as 2640 mg/L. The costing estimations revealed a negligible difference in plant operational requirements. The observed results helped us to conclude that pH, TDS, and TN have attained their desired limits according to the standards. Furthermore, we also observed that *vetiver* was slightly more efficient than *colocasia* by comparing the characteristics. It is worth mentioning that other parts of these two investigated plants, e.g., stem, root, and leaves, are also quite useful for other purposes.

3.2. Treatment Efficiency of Colocasia and Vetiver

The following results discuss the treatment efficiencies of the *colocasia* and *vetiver* plants, which were calculated based on the overall characteristics (Table 2). From these values, it can be suggested that root zone technology is reliable up to a reasonable extent and treated effluent can be used for non-potable purposes, such as gardening and horticulture practices.

Table 2. Comparison of colocasia and vetiver plants.

Parameters Analyzed	Detention Time (d)	*Colocasia*	*Vetiver*
	5	12.5	25
pH	10	35	45
	15	52.5	80
	5	19.7	20.86
TDS (mg/L)	10	56.9	57.3
	15	71.7	72.1
	5	50.46	51.3
TSS (mg/L)	10	60.6	61.2
	15	63.6	64.5
	5	7.8	6.7
TN (mg/L)	10	40.4	49.4
	15	57.3	59.5
	5	21.6	30
Turbidity	10	50	50.6
	15	59.3	71.6
	5	39.7	39.3
(NTU)	10	60.8	61.2
	15	81.5	81.7
	5	18.3	19.6
BOD (mg/L)	10	47.1	47.4
	15	68.9	69.1

Figure 6 shows the treatment efficiency of the *colocasia* plant. The pH change after 5, 10, and 15 days was observed to be 12.5%, 35%, and 52.5%, respectively. These results suggested considerably insignificant changes in TDS. The TDS removal after 5, 10, and 15 days was observed to be 19.7%, 56.9%, and 71.7%, respectively. The TSS reduction after 5, 10, and 15 days was 50.46%, 60.6%, and 63.6%, respectively. The TN reduction after 5, 10, and 15 days was calculated as 7.8%, 40.4%, and 57.3%, respectively. Overall, it can be stated that TN is also reduced by RZT. The turbidity results also change in RZT, by 21.6%, 50%, and 59.3% after 5, 10, and 15 days, respectively. The BOD reduction in root zone technology after 5, 10, and 15 days was 39.7%, 60.8%, and 81.5%, respectively. COD values reduced after 5, 10, and 15 days by 8.3%, 47.1%, and 68.9%, respectively. Hence, it was observed that both BOD and COD decreased significantly in the investigated treatment approach. Furthermore, the cost estimations revealed that RZT has significant potential for techno-economic application.

Figure 7 shows the treatment efficiency of the RZT approach for the *vetiver* plant. The percentage change in pH after 5, 10, and 15 days was calculated as 25%, 45%, and 80%, respectively. The change in TDS levels in RZT after 5, 10, and 15 days was 20.86%, 57.3%, and 72.1%, respectively. The TSS values were also observed to be reduced by using this technology. The TSS reduction after 5, 10, and 15 days was observed as 51.3%, 61.2%, and 64.5%. TN was also reduced in the investigated approach. The values were found to be 6.7%, 49.4%, and 59.5% after 5, 10, and 15 days, respectively. The turbidity levels also showed variability in RZT, with a reduction of 30%, 50.6%, and 71.6% after 5, 10, and 15 days, respectively. The BOD values were reduced in RZT after 5, 10, and 15 days by 39.3%, 61.2%, and 81.7%, respectively. The COD reduction after 5, 10, and 15 days was found to be 19.6%, 47.4%, and 69.1%, respectively. Collectively, it can be stated that both BOD and COD decreased during the treatment. The cost for setting up the root zone technology with a *vetiver* plant is not much higher; thus, the proposed technology may be a promising solution for industrial effluent treatment [27].

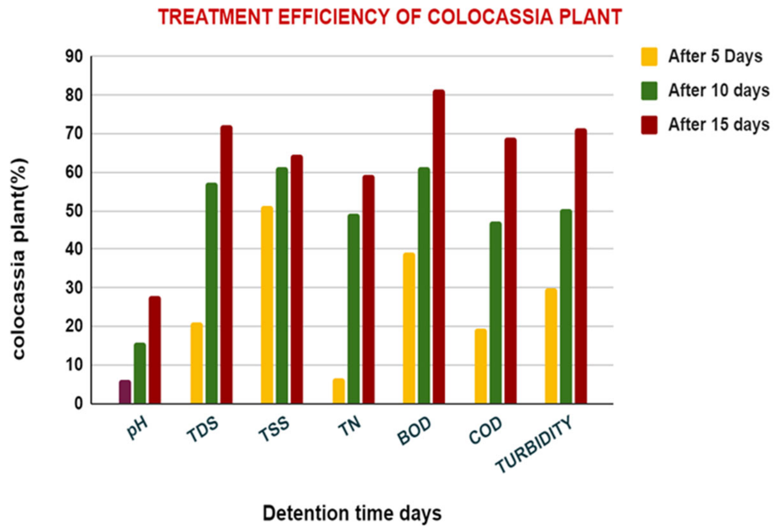

Figure 6. Treatment efficiency of colocasia plant.

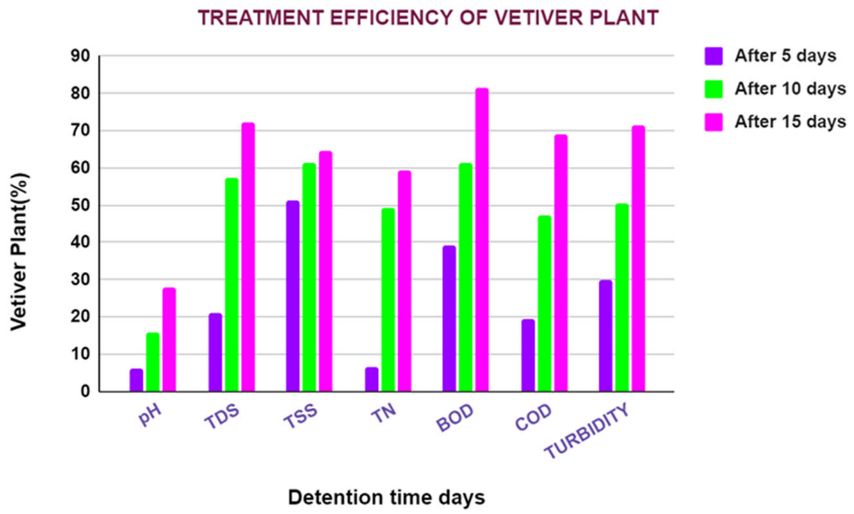

Figure 7. Treatment efficiency of vetiver plant.

Using hybrid reed bed technology, Parmar et al. [28], conducted an experimental study on the post treatment of dairy wastewater, their study provides information about dairy waste treated using a hybrid reed plant. According to this study, the hybrid reed bed system was very efficient in removing BOD by up to 14 mg/L and COD up to 110 mg/L after 36 h of detention time, with removal efficiencies of 97% for BOD and 92% for COD for dairy effluent. TDS and TSS reductions were generally not noticeable. The pH of the dairy waste sample was initially more alkaline; however, because of the techniques used, the pH was significantly raised and became much closer to neutral. One advantage was that within a year of operation, the root zone system's wastewater efficiency was notable. It was extremely cost-effective, low-maintenance, and environmentally friendly. In a tropical developing nation such as India, well-designed and adequately maintained and operated root zone systems can be a practical technology in the future. However, it could very well be claimed that the future of RZT is still being explored and developed, and significant technological barriers remain.

4. Conclusions

The latex industry, in which rubber is the primary product, is one of the industries releasing the most pollutants. Implementing RZT for effluents in this industry will not only minimize the water footprint of products but also promote the circular economy approach. Developing and transferring RZT to industries can reduce water pollution and consequently mitigate environmental pollution to a greater extent. The results of this study helped the authors to conclude that pollutant levels in latex industrial wastewater can be reduced to a great extent using RZT technology. Root zone efficiency can be appreciably achieved within 15 days of continuous operation. In this study, a total of five plants were employed in an RZT system with a single reactor. The aqueous sample analysis results revealed that the plants can be helpful in achieving a maximum of 80% pollutant removal efficiency. Almost similar values of COD, of 2655 mg/L and 2640 mg/L, were obtained with the *colocasia* and *vetiver* plants, respectively. After 5, 10, and 15 days of operation of RZT, the reduction in turbidity levels observed was as 21.6%, 50%, and 59.3% for *colocasia*, and 30%, 50.6%, and 71.6% for *vetiver*, respectively. The BOD values were slightly higher (920 mg/L) for *colocasia* than for *vetiver*.

We obtained this treatment result without expending considerable energy, which provides a major link to a circular economy. The treatment method was intended to achieve energy self-sufficiency to ensure alignment with circular economy concepts. This stage prioritizes the need for awareness and optimized feasibility of the solution. To the best of our knowledge, this is the first approach to this process that focuses on economic viability.

The successful application of RZT can be helpful in ensuring the sustainability of small towns, cities, industries, and other institutions that are expected to produce effluents with similar characteristics. Further studies on more plant species can be performed to improve this technology. Soil tests will also be an excellent option for understanding concepts of reed absorption mechanisms. Further, incorporating modeling in agricultural systems will enhance future studies.

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