"Study on Root Zone Technology on Treating Domestic Wastewater"

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Abstract - *An The study examines how effective Root Zone Technology (RZT) is as a sustainable, low-cost, eco-friendly way to treat domestic wastewater. This approach is especially useful in areas where traditional sewage treatment plants struggle due to high operating costs and maintenance problems.*

Researchers collected wastewater samples from the Degaon STP region in Solapur and treated them using a laboratory-scale Horizontal Subsurface Flow (HSSF) constructed wetland system. This system was planted with chosen macrophytes. The experiment looked at how different hydraulic retention times (HRTs) and plant species affected the removal of key pollutants. These pollutants included BOD, COD, TSS, color, sulfates, total nitrogen, and ammonical nitrogen.

The results showed a clear improvement in effluent quality with longer HRTs. Plant species like Canna indica, Typha latifolia, and Phragmites australis helped reduce pollutants through their ability to filter, break down microbes, and absorb nutrients.

Overall, the study supports the idea that RZT is a promising decentralized treatment option. It can produce treated water that is suitable for irrigation and landscaping. This method also aids in sustainable wastewater management and protects the environment in semi-urban and rural areas.

Key Words: Root Zone Technology (RZT), Constructed Wetlands, Domestic Wastewater, Hydraulic Retention Time (HRT), Pollutant Removal Efficiency, Macrophytes, Biochemical Oxygen Demand (BOD), Sustainable Wastewater Treatment

1.INTRODUCTION

1.1 Background Of The Study

This Water is one of the most vital natural resources for all forms of life on Earth (Meshram et al. 2020). It plays a key role in maintaining ecological balance, supporting agricultural productivity, industrial development, and human health (Survase et al. 2023). However, rapid urbanization, industrialization, and population growth have significantly harmed the quality and availability of freshwater resources (Desai et al. 2014). The production of large amounts of domestic and industrial wastewater has become one of the biggest environmental challenges of the 21st century (https://ln.run/UQYws).

According to global estimates by the United Nations Environment Programme (UNEP), nearly 80% of wastewater generated worldwide is discharged untreated into natural water bodies. This untreated discharge pollutes rivers, lakes, and groundwater aquifers. It leads to eutrophication, the spread of water-borne diseases, and severe ecological damage (Survase et al. 2023). In developing nations like India, the rate of urban growth far outpaces infrastructure development, making wastewater management a critical issue (Desai et al. 2014).

Domestic wastewater, also known as sewage, includes a mix of water and waste from households, such as human excreta, food scraps, soaps, and detergents (Meshram et al. 2020). If untreated, it can spread pathogens and toxic materials, making the water unsafe for human use or irrigation. The Central Pollution Control Board (CPCB, 2015) reports that a significant amount of sewage generated in Indian cities goes untreated due to limited treatment capacity and poor maintenance of existing facilities.

The city of Solapur in Maharashtra illustrates this growing problem. With a population over one million and daily wastewater generation of about 88 million liters (MLD), the city lacks sufficient treatment infrastructure (Meshram et al. 2020). The current Degaon Sewage Treatment Plant (STP), meant for 54 MLD, has been out of service since 1985. This has led to untreated sewage being directly discharged into the Shelgi Nallah, which flows into the Sina River (Meshram et al. 2020). This situation has caused considerable pollution of surface and groundwater sources, negatively impacting the health and livelihoods of communities like Kawathe and Gulwanchi villages, who rely on these waters for irrigation and domestic use (https://ln.run/BgGsu).

Given the limitations of traditional wastewater treatment systems, which often consume a lot of energy, require complex operations, and are costly, there is a need to explore sustainable, low-cost, and eco-friendly alternatives (Meshram et al. 2020). Root Zone Technology (RZT), a type of constructed wetland system, has emerged as a practical solution that combines biological and ecological processes for effective wastewater treatment (Survase et al. 2023).

1.2 Need For Sustainable Wastewater Treatment

Water scarcity and pollution have reached concerning levels, particularly in semi-arid regions like Solapur (https://ln.run/M-Mm0). The traditional reliance on large sewage treatment plants is becoming unsustainable for several reasons:

a. High Energy and Operation Costs. Traditional methods like Activated Sludge Process (ASP) and Sequencing Batch Reactors (SBR) need constant aeration, pumping, and skilled operators (Survase et al. 2023).

b. Complex Infrastructure. These systems require expensive civil, mechanical, and electrical installations, which small municipalities often cannot afford (Meshram et al. 2020).

c. Sludge Disposal Problems. Conventional plants generate large amounts of sludge that need additional handling and disposal (Survase et al. 2023).

d. Frequent Breakdowns and Maintenance. Mechanical parts often fail due to poor operation and maintenance in Indian conditions (Meshram et al. 2020).

e. Resource Wastage. Important nutrients and biomass are lost instead of being recycled for agriculture (Meshram et al. 2020).

In comparison, Root Zone Technology (RZT) provides a nature-based, decentralized, and energy-efficient way to treat wastewater. It is especially suitable for small towns, rural areas, and institutions (Meshram et al. 2020). RZT uses natural filtration and bioremediation in the root zones of specific wetland plants. These plants, along with soil and microbes, serve as a biological filter, effectively removing pollutants from wastewater (Gajendran et al. 2017).

Therefore, implementing RZT not only helps reduce environmental harm but also supports sustainable development goals (SDGs) by encouraging resource recovery, groundwater recharge, and the reuse of treated water (Shinde et al. 2019).

1.3 Concept And Working Principle Of Root Zone Technology

Root Zone Technology (RZT), also called Constructed Wetland (CW) or Reed Bed Technology, is a natural, low-cost way to treat wastewater. It uses wetland plants, soil, and microorganisms to remove contaminants (Meshram et al. 2020).

The treatment happens in a specially designed bed that contains gravel, sand, and soil. This bed is planted with aquatic or semi-aquatic species like Canna indica, Phragmites australis, and Typha latifolia (Survase et al. 2023). These plants are essential for maintaining oxygen flow within the system. They support both aerobic and anaerobic microbial processes around their roots (the rhizosphere) (Survase et al. 2023).

The primary processes in RZT include:

- Physical Processes: Filtration, sedimentation, and adsorption of suspended solids and colloidal matter (Meshram et al. 2020).

- Chemical Processes: Precipitation of metals and phosphates, ion exchange, and oxidation-reduction reactions (Survase et al. 2023).

- Biological Processes: Microbial breakdown of organic pollutants, nitrification, denitrification, and plant absorption of nutrients (Meshram et al. 2020).

There are two main setups (Survase et al. 2023):

a. Horizontal Subsurface Flow (HSSF): Wastewater flows horizontally through the bed, just below the surface. This design reduces odors and mosquito problems.

b. Vertical Subsurface Flow (VSSF): Wastewater is spread on top and then moves vertically downward through the media.

This study focuses on the HSSF system, which offers longer retention time, improved microbial activity, and better removal of organic matter (Survase et al. 2023).

1.4. Advantages Of Root Zone Technology

Root Zone Technology (RZT) offers several environmental, technical, and economic benefits compared to traditional wastewater treatment systems. These benefits make it a strong option for sustainable wastewater management, particularly in developing countries (Meshram et al. 2020).

Key advantages include:

- Low Capital and Operation Costs: RZT uses locally available materials like gravel and sand, which significantly lowers the initial setup cost (Survase et al. 2023).

- Energy Efficiency: It operates without mechanical aeration, cutting energy consumption by 70 to 80% compared to conventional methods (Survase et al. 2023).

- Simple Maintenance: The system does not need skilled workers and functions well under different weather conditions (Vymazal 2010).

- Odor-Free Operation: Since wastewater flows below the surface, there are no bad smells or mosquito breeding problems (Dotro 2017).

- Minimal Sludge Generation: Very little sludge is created, removing the need for complicated sludge treatment and disposal systems (Rahaman & Baskar 2009).

- Resource Recovery and Water Reuse: Treated water can be used for irrigation, gardening, or landscaping, and plant biomass can be used for compost or biofuel (Kannan 2017).

- Eco-Friendly and Aesthetic: It improves local biodiversity, creates green spaces, and blends naturally into the environment (Survase et al. 2023).

- Decentralization Potential: RZT can be set up as small modular systems suitable for housing complexes, institutions, and rural communities (Survase et al. 2023).

1.5. Status Of Wastewater Management In Solapur

Solapur, in the semi-arid region of Maharashtra, faces serious water shortages and problems with wastewater pollution. The Solapur Municipal Corporation (SMC) produces about 88 million liters of wastewater each day, but the current treatment capacity is not enough.

The Degaon Sewage Treatment Plant (STP) started in the early 1980s with a design capacity of 54 million liters per day, but it has been out of service for many years. As a result, untreated sewage is released directly into natural drainage channels like the Shelgi Nallah, which later pollutes the Sina River (Solapur Municipal Corporation).

This untreated waste has caused:

- Pollution of irrigation water sources that farmers use.

- Contamination of groundwater aquifers with nitrates and ammonia.

- Negative effects on soil fertility and crop productivity.

- Rise of waterborne diseases in nearby communities.

Villages such as Kawathe and Gulwanchi have seen decreased crop yields and poorer soil health due to long-term irrigation with untreated wastewater (Solapur Municipal Corporation). Therefore, fixing the Degaon STP with a low-cost treatment method like RZT is essential for protecting the environment and public health (Survase et al. 2023).

1.6. Mechanism Of Pollutant Removal In Rzt

Pollutant removal in Root Zone Technology systems happens through a mix of physical, chemical, and biological processes. These methods work together to achieve high treatment efficiency (Survase et al. 2023).

Table 1.1: Mechanisms Of Pollutant Removal In RZT

Process Type	***Mechanism***	***Pollutants Removed***
Physical	Sedimentation, Filtration, Adsorption	Suspended solids, Color, Turbidity
Chemical	Precipitation, Ion exchange, Redox reactions	Phosphates, Sulfates, Heavy metals
Biological	Microbial degradation, Nitrification, Denitrification, Plant uptake	BOD, COD, Nitrogen compounds

• Microbial degradation: Microorganisms break down organic pollutants into simpler compounds, which lowers BOD and COD (Vipat et al. 2008).

• Plant uptake: Plants take in nutrients like nitrates and phosphates, helping to prevent eutrophication (Vipat et al. 2008).

• Rhizosphere oxygenation: Plant roots release oxygen, which improves aerobic degradation and keeps redox balance (Vipat et al. 2008).

Together, these actions make RZT very effective for treating domestic wastewater and produce effluent that is suitable for reuse (Vipat et al. 2008).

1.7. Global And Indian Experience With Rzt

Root Zone Technology started in Germany in the 1970s and has been successfully used in several countries, including Denmark, Egypt, Hungary, and the United States. In these countries, RZT systems have achieved removal efficiencies of over 80 to 90% for BOD and COD (Meshram et al. 2020).

In India, the National Environmental Engineering Research Institute (NEERI) took the lead in applying RZT in the 1990s. Successful installations include:

• Bhopal (Madhya Pradesh): A pilot plant at Ekant Park that treats 70,000 L/day of domestic sewage effectively.

• Ahmedabad (Gujarat): A campus-based RZT system that treats institutional wastewater.

• Pune and Solapur (Maharashtra): College and residential applications that show high pollutant removal efficiencies.

Studies by Meshram et al. (2020), Zafar et al. (2021), and Gajendran et al. (2022) reported average pollutant removal efficiencies of 85 to 95% for BOD and 80 to 90% for COD. This demonstrates RZT's effectiveness for decentralized wastewater management in India.

2. Literature Review

The brief introduction of various studies undertaken to investigate the application of root zone technology, is discussed in the following sections.

Survase et al. (2023) studied “Waste Water Treatment by Root Zone Technology (Colocasia Roots).” Wastewater treatment is an important environmental issue that requires sustainable and cost-effective solutions. Root zone technology (RZT) using Colocasia roots has emerged as a promising method for efficient wastewater treatment. This abstract gives an overview of RZT's application with Colocasia roots and its potential benefits. The goal of this study is to evaluate how effective Colocasia roots are in wastewater treatment with RZT. Colocasia, also known as taro or elephant ear, has strong roots and unique traits that make it suitable for wastewater treatment. These include high porosity and a large surface area that help remove pollutants. RZT directs wastewater through a constructed wetland containing Colocasia roots. As the wastewater moves through the root zone, physical, chemical, and biological processes occur, leading to the removal or transformation of contaminants. Colocasia roots work as a physical barrier, capturing suspended solids and organic matter while encouraging the growth of helpful microorganisms that assist in breaking down pollutants. Studies have shown that RZT with Colocasia roots is effective in treating various types of wastewater, such as domestic, agricultural, and industrial effluents. This technology can remove pollutants like nitrogen, phosphorus, heavy metals, and organic compounds. Additionally, RZT with Colocasia roots has benefits like low energy use, no harsh chemicals, and the possibility of reusing wastewater for agriculture or landscaping. RZT with Colocasia roots offers a promising and eco-friendly method for wastewater treatment. Its ability to filter contaminants, support biological degradation, and promote plant-microorganism interactions makes it a better option than traditional methods. Parth More research and application of this technology can greatly help reduce water pollution and support sustainable water management practices.

Gajendran et al. (2022) studied "Ensuring Sustainability via Application of Root Zone Technology in a Rubber Product Industry: A Circular Economy Approach." They found that rapid urbanization has led to the degradation of water quality and availability. Urban development and its activities pollute freshwater by generating different types of waste. Root Zone Technology (RZT) has been successfully adopted in several countries to support sustainable development. RZT enables the integration of automated processes into an artificial soil ecosystem. The main goal of this study was to create a natural and effective water treatment process for industrial effluents using RZT. This technology uses layers of coarse and fine aggregates, charcoal, sand, and planted filter beds with compost media to treat effluents. The system is easy to set up, has low maintenance, and low operational costs. Selected plants achieved 50-80% pollutant removal. RZT significantly reduces the characteristics of effluents, such as chemical oxygen demand, biochemical oxygen demand, pH, color, TSS, TDS, BOD, and COD. Further studies should explore more plant species to enhance this technology. Soil tests can also help understand the mechanisms of reed absorption. Additionally, including modeling in agricultural systems would benefit future studies.

Kumar et al. (2021) studied "First comparison of conventional activated sludge versus root-zone treatment for SARS-CoV-2 RNA removal from wastewaters: Statistical and temporal significance." They discovered that during the initial pandemic phase, wastewater treatment facility effluents were mostly free of Severe Acute Respiratory Coronavirus 2 (SARS-CoV-2) RNA, suggesting conventional wastewater treatments were generally effective. However, there is limited data on i) the comparative effectiveness of various treatment processes for SARS-CoV-2 RNA removal and ii) how the removal efficacy of a specific treatment process varies over time amid active COVID-19 cases. This work compares the removal effectiveness of conventional activated sludge (CAS) and root zone treatments (RZT) using weekly wastewater surveillance data from forty-four samples over two months. The average genome concentration was higher in the inflow of the CAS-based wastewater treatment plant (WWTP) in the Sargasan ward (1.25 × 10^3 copies/L) than in the RZT-based WWTP (7.07 × 10^2 copies/L) at an academic institution in Gandhinagar, Gujarat, India. ORF 1ab and S genes were more sensitive to treatment, showing significant reduction ($p < 0.05$) compared to N genes ($p > 0.05$). CAS treatment showed better RNA removal effectiveness ($p = 0.014$) than RZT ($p = 0.032$). Multivariate analyses suggest that calculating effective genome concentration should consider the presence or absence of multiple genes. The current study notes that treated effluents are not always free from SARS-CoV-2 RNA, and the removal effectiveness of any WWTP may vary over time due to fluctuations in active COVID-19 cases and genetic material accumulation. Disinfection appears less effective than adsorption and coagulation processes for SARS-CoV-2 removal. The results highlight the need for further research into the mechanisms behind SARS-CoV-2 removal through different treatment processes, taking solid-liquid partitioning into account.

Meshram et al. (2020) studied "Waste Water Treatment by using Root Zone Technology: Using Colocasia Plant." They noted that water quality on Earth suffers due to increasing human development activities that deplete and harm water resources. Rapid urbanization has polluted fresh water bodies with rising domestic waste, sewage, and industrial waste. This paper reviews Root Zone Technology as a low-cost and eco-friendly method for wastewater treatment. The root zone treatment system utilizes a natural approach to effectively treat domestic and industrial effluents. This technology is successfully implemented in several countries, including those in Europe and America. The wetland bed is divided into three zones: soil layer, sand layer, and aggregate layer. Colocasia trees are planted in the top layer. When wastewater passes through the upper and middle layers, suspended solids are trapped in the soil and sand pores, while remaining solids are removed with the help of bacteria. This technology is easy to operate, requires minimal installation, has low maintenance, and is more beneficial compared to expensive conventional treatment systems. There is a need to fully utilize this technology in developing countries like India to reap its benefits and support sustainable development.

Gohil et al. (2017) studied "Introduction to Waste Water Treatment by Root Zone Technique." They found that increasing urbanization and human activities affect the quality and quantity of water resources. This leads to the pollution of freshwater bodies due to rising domestic waste, sewage, and industrial waste generation. This paper reviews the Root Zone Treatment System, which consists of planted filter beds made of soil, gravel, sand, and fine aggregate. This technique uses a natural way to effectively treat domestic and industrial effluents. RZTS is well-known in temperate climates; it is easy to operate, requires minimal installation, has low maintenance and operational costs, and incorporates self-regulating dynamics of an artificial soil ecosystem. This technology has been successfully implemented in various countries. Constructed wetlands are now recognized as an affordable eco-technology, especially advantageous compared to costly conventional treatment systems. There is a need to maximize this technology's use in developing countries like India to gain its benefits and encourage sustainable development.

Shinde et al. (2019) worked on "Waste Water Treatment by Root Zone Technology." Their paper discusses the theoretical basis of wastewater treatment in the Rhizosphere of wetland plants, known as the Root Zone Method, and presents initial results from eight treatment plants in Denmark. Mechanically, treated wastewater flows horizontally through the Rhizosphere of wetland plants. As the wastewater passes through, it is cleaned through microbiological degradation along with physical and chemical processes. The wetland plants supply oxygen to the microorganisms in the rhizosphere and help stabilize the soil's hydraulic conductivity. Nitrogen is removed through denitrification, while phosphorus and heavy metals are captured in the soil. The initial data from Denmark shows that, regarding BOD, Root Zone Plants nearly meet conventional secondary treatment standards within the first growing season (removal efficiency 51-95%). However, there is still little information about the removal processes for nitrogen, the effect of soil type, and the required surface area to load ratio.

Kalpana et al. (2014) conducted a study on "Wastewater Treatment through Root Zone Technology with Special Reference to Shahpura Lake of Bhopal (M. P.), India." Water quality is declining due to increasing human development activities that deplete and harm water resources. Rapid urbanization has led to the pollution of freshwater bodies due to rising domestic waste, sewage, and industrial waste generation. This study examined the effectiveness and feasibility of a Horizontal surface flow constructed wetland/Root Zone Unit built by the Environmental Planning & Coordination Organization (EPCO) at Ekant Park, Bhopal. The study collected wastewater samples from the inlet and outlet of the Root Zone System at Ekant Park, Bhopal, from June 2011 to May 2012. Some physicochemical parameters, namely dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate, and phosphate, were analyzed using standard methods. The results indicated that the Root Zone System is effective, and the treated water can be used for activities like washing clothes, fishing, swimming, and irrigation. Rapid urbanization continues to pollute fresh water bodies due to increased domestic waste, sewage, and industrial waste generation. This study investigated the effectiveness and feasibility of the Horizontal surface flow constructed wetland/Root Zone Unit built by EPCO at Ekant Park, Bhopal.

Md. Zafar et al. (2021) studied "Waste water management by root zone technology". The term root zone refers to the interactions among bacteria, the roots of wetland plants, soil, air, sunlight, and water. Root zone treatment is a method for purifying wastewater as it moves through an artificially created wetland area. It is an effective and reliable method for secondary and tertiary treatment. Various physical, chemical, and biogeochemical processes, such as sedimentation, absorption, and nitrification, along with uptake by wetland plants, help remove pollutants. Root zone systems work best for schools, hospitals, hotels, and smaller communities. This research aims to assess the efficiency of the wetland plant Phragmites australis in treating wastewater generated within the SRM University premises. A pilot wetland unit measuring 1.5m × 0.6m × 0.3m was built on campus. Phragmites australis plants were grown in the field using fresh water. Three rows of plants were transplanted into the pilot unit, where they were supplied with wastewater from hostels and other campus buildings. Raw and treated wastewater were collected periodically and tested for quality. This pilot unit reduced the concentrations of TSS, TDS, TN, TP, BOD, and COD by an average of 90%, 77%, 85%, 95%, 95%, and 69%, respectively. The root zone system meets tertiary treatment standards without operating costs and with low maintenance costs. It improves the landscape, provides a habitat for birds, and does not cause odor issues.

Bandal et al. (2018) worked on "Root Zone Technology for Campus Waste Water Treatment". They found that water quality on earth is declining due to ongoing human development that overuses and impacts water resources. Rapid urbanization has polluted freshwater bodies because of increased domestic and industrial waste. This study examined the effectiveness and feasibility of a vertical surface flow constructed Root Zone Unit located at the Dattakala College canteen in Swami Chincholi. They collected wastewater samples from both the inlet and outlet of the Root Zone System at the canteen. Some physio-chemical parameters like dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH, and alkalinity were analyzed using standard methods. The results showed that the Root Zone System operates effectively and that treated water can be used for activities like washing clothes, fishing, swimming, and irrigation. This RZT project could expand into side businesses like aquaponics and organic farming because of the large amount of clean water available from the RZT plant. The treated water can be used in an aquaponic tank for fish production, while the waste contents can be utilized for organic farming.

Kannan (2017) conducted a study on "Root Zone Technology Used for Treatment of Campus Waste Water". He noted that India faces various environmental problems, including water scarcity and safe disposal of wastewater. Urbanization and population growth are reducing our natural resources. The demand for water is rising continuously. In this context, wastewater can be treated economically using Root Zone Technology and plants like Azolla, with parameters analyzed according to Indian standards. Our campus maintains about 0.5 acres of garden area daily, consuming around 10,000 liters of water per day for gardens and trees. Therefore, I pursued this project, using treated wastewater for gardening and agricultural purposes. Raw and treated wastewater were collected periodically and tested for quality, showing reductions in the concentrations of TSS, TDS, TN, TP, BOD, and COD.

Desai et al. (2014) studied "Root-zone technology as energy efficient and cost effective for sewage water treatment". They noted that designing, constructing, and operating a sewage treatment plant (STP) requires a multi-disciplinary approach. Several conventional methods exist for designing STPs. These processes are either aerobic, anaerobic, or a combination, and often involve numerous mechanical and electrical components, requiring substantial energy. The growing energy demand makes STP design, operation, and maintenance challenging. Conventional sewage treatment methods can be improved using advanced technologies. However, root zone technology developed by the National Environmental Engineering Research Institute effectively treats sewage. Studies on nine STPs at various locations found it used only 20% of the energy compared to traditional treatment plants.

Ravaler et al. (2015) studied "Root Zone Technology: Reviewing its Past and Present". Their research found that increasing urbanization and human activities impact the quality and quantity of water resources. This leads to pollution in freshwater bodies due to rising domestic and industrial waste. The paper reviews the Root Zone Treatment System (RZTS), which uses planted filter beds with soil. This technology naturally and effectively treats domestic and industrial effluents. RZTS are well-suited for temperate climates, are easy to operate, and have low installation, maintenance, and operational costs. They utilize the self-regulating dynamics of an artificial soil ecosystem. Constructed wetlands are now recognized as a low-cost eco-technology, offering benefits over expensive conventional treatment systems. There is a need to maximize this technology in developing countries like India for sustainable development. Root Zone Technology addresses the water pollution challenges of the modern industrialized world. The growth of wetland plants, known as reeds, in specially designed beds provides an eco-friendly approach to protect nature.

Rahaman et al. (2009) studied "Root Zone Technology for Campus Waste Water Treatment". They found that root zone treatment is an effective method for purifying wastewater as it flows through artificially created wetland areas. It reliably removes pollutants through various physical, chemical, and biogeochemical processes, including sedimentation, absorption, and nitrification, along with uptake by wetland plants. This pilot unit reduced TSS, TDS, TN, TP, BOD, and COD concentrations by averages of 90%, 77%, 85%, 95%, 95%, and 69%, respectively. The root zone system meets tertiary treatment standards without operating costs and with low maintenance expenses.

Preetha et al. (2009) studied "Rhizosphere Treatment Technology for Community Waste Water Treatment". They concluded that rhizosphere treatment is often the best choice for treating or pre-treating wastewater due to its low maintenance cost, simplicity of operation, and high efficiency. It also enhances local aesthetics and conserves local flora and fauna. Rapid urbanization has increased pressure on infrastructure, resulting in poor services from local authorities. Untreated sewage flowing through channels joins rivers, creating a significant risk of river pollution. They investigated the effectiveness and techno-economic feasibility of the RZTS (Root Zone Treatment System) and its modifications.

Allgoo et al. (2018) studied "Root Zone Technology". They found that increasing urbanization and human activities negatively impact the quality and quantity of water resources, leading to the pollution of freshwater bodies due to rising domestic and industrial waste. This research reviews the Root Zone Treatment System (RZTS), involving planted filter beds made of soil. The technology offers a natural method for treating domestic and industrial effluents effectively. RZTS are recognized for their ease of operation, low installation, maintenance, and operational costs, incorporating self-regulating dynamics of artificial soil ecosystems. Constructed wetlands are considered a low-cost eco-technology, especially compared to traditional treatment systems. This technology should be fully exploited in developing countries like India for sustainable development. The study assessed the effectiveness and feasibility of the horizontal flow constructed wetland root zone unit, collecting samples of wastewater from the inlet and outlet of the root zone system between March 2017 and June 2017. Analysis of some physiochemical parameters including dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), turbidity, and pH was conducted using standard methods. The results showed that root zone technology effectively reduced pollutants by up to 60%, allowing for its direct use in washing clothes, fishing, swimming, and irrigation. The remaining pollutants can be moderately cleansed using modern practices, which could minimize operational costs.

Ijare et al. (2019) conducted a study on "Waste Water Treatment by Root Zone Technology". Their paper describes the theoretical framework of wastewater treatment in the rhizosphere of wetland plants, known as the Root Zone Method, alongside early experiences from eight treatment plants in Denmark. Mechanically treated wastewater flows horizontally through the rhizosphere of wetland plants. During this process, microbiological degradation, and physical and chemical processes clean the wastewater. The wetland plants provide oxygen to heterotrophic microorganisms in the rhizosphere and stabilize the soil's hydraulic conductivity. Nitrogen is removed through denitrification, while phosphorus and heavy metals are retained in the soil. The initial experiences from Denmark indicated that Root Zone Plants nearly meet conventional secondary treatment standards regarding BOD, achieving removal efficiencies of 51-95% from the first growing season. However, limited information exists on nitrogen removal processes, soil type effects, and the necessary surface area to loading ratio.

Gomez et al. (2020) conducted an experiment titled "Horizontal Flow Constructed Wetland for Greywater Treatment and Reuse: An Experimental Case." In the upcoming years, water stress is expected to increase significantly due to rising water consumption and the noticeable effects of climate change. Greywater (GW) has been explored as an alternative water source in dry areas. While there is no single best way to treat GW, constructed wetlands have shown to be effective. This paper presents results from treating real GW using a horizontal flow constructed wetland (HFCW) for over four months. In the initial laboratory-scale test, Phragmites australis, Carex oshimensis, and Cyperus papyrus were assessed separately and produced very similar results. In the second phase, pilot-scale tests were performed to verify performance on a larger scale and assess the influence of hydraulic retention time, achieving high removal rates for turbidity (>92%), total suspended solids (TSS) (>85%), chemical oxygen demand (COD) (>89%), and five-day biological oxygen demand (BOD5) (>88%). The paper also compares the results from the pilot-scale HFCW to recommendations from the World Health Organization and the European Union.

Manna (2018) studied "Treatment of Gray Water for Reusing in Non-potable Purposes to Conserve Water in India." The scarcity of fresh water is a major challenge in various regions of India, prompting the need for sustainable water conservation efforts. The natural supply of potable water is insufficient to meet daily demands. People are looking for different solutions to address this serious issue. Treating and reusing gray water is one promising approach to conserve water. Gray water comes from showers, baths, sinks, kitchens, and washing machines, excluding toilet waste. It can be treated through physical, chemical, biological, or natural methods, or a combination of these. Treated gray water can be reused for tasks like toilet flushing, irrigation, floor washing, and car washing. This paper presents a statistical analysis of total domestic water use, gray water production, and treated water generation. The analysis indicates that treated water from light gray water in homes can meet up to 35% of the non-potable domestic demand, such as toilet flushing and garden irrigation. For mixed gray water, an additional 20-25% of treated water can be used for ground replenishment or other non-potable uses. The study shows that recycling and reusing treated gray water could significantly reduce fresh water consumption daily.

Kalmegh et al. (2019) conducted "Experimental Analysis of Wastewater in Shahu Campus of Pune City." They highlighted that water pollution of surface water bodies is a significant environmental issue in India. The main source of this pollution is untreated sewage from residential, commercial, and institutional activities. There is a large gap between wastewater generation and the treatment facilities available due to limited funds and space. Wastewater treatment poses challenges today. This study aims to improve conventional Root Zone technology. It focuses on cost-effective wastewater treatment using Root Zone Technology. The research took place at Jedhe More Hostel on "ABMSP'S" Campus in Pune. The study examined the effectiveness and feasibility of wastewater treatment in the hostel. Key physio-chemical parameters, such as biological oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen (DO), were analyzed using standard methods. After treatment, the water quality allows for recreational use. The findings indicate that the Root Zone system effectively treats wastewater.

Prasad et al. (2017) investigated "Constructed Wetland as an Effective Treatment Method for Domestic Wastewater Treatment." The study noted that rapid urbanization and industrial growth have led to severe environmental pollution over the past few decades, negatively impacting nature. The goal was to find an economical method to treat domestic wastewater and to compare the effectiveness of naturally aerated and artificially aerated constructed wetlands. Two lab-scale models were set up in buckets measuring 400mm x 300mm, with one model equipped with an artificially aerated system. Wastewater parameters were checked after 12, 24, and 48 hours. This study was conducted in the Mundhwa area, using a lab-scale model. Parameters such as color, odor, pH, COD, and DO were measured. The results showed that the artificially aerated constructed wetland had more treatment efficiency than the naturally aerated one. The treated wastewater was odorless, clear, and changed from blackish to colorless.

Raut et al. (2020) studied “Waste Water Treatment Using Root Zone Technology: Using Colocasia Plant.” They noted that water quality on Earth is suffering due to increasing human activities, which have depleted both the quality and quantity of water resources. Rapid urbanization has led to the pollution of freshwater bodies from domestic waste, sewage, and industrial waste. This paper reviews Root Zone Technology as a low-cost, eco-friendly method for treating wastewater. This system uses a natural approach to treat both domestic and industrial effluents effectively. The technology has been successfully implemented in several countries, including those in Europe and America. The wetland bed consists of three layers: soil, sand, and aggregate. Colocasia trees will be planted on the top layer. As wastewater passes through, all suspended solids are trapped in the soil and sand, while bacteria help remove the remaining solids. This technology is easy to use, requires less installation and maintenance, and is preferable to expensive conventional treatment systems. There is a pressing need to maximize the use of this technology in developing countries like India for sustainable development.

Vipat et al. (2008) conducted research on "Efficacy of Root Zone Technology for Treatment of Domestic Wastewater: Field Scale Study of a Pilot Project in Bhopal (MP), India." Urban water bodies in tropical developing countries are heavily affected by domestic wastewater and sewage, primarily due to the growing gap between wastewater generation and the lack of affordable resources to address the issue with conventional technologies. Therefore, biological systems may offer a novel solution for managing water bodies sustainably. Root zone technology operates as a natural biological system relying solely on solar energy, making it low-cost with minimal operation and maintenance needs. This paper evaluates the performance of a field-scale Horizontal Subsurface Flow constructed Wetland/Rootzone demonstration unit built by the Environmental Planning & Coordination Organisation (EPCO) at Ekant Park, Bhopal. This pilot project treats 70,000 liters of wastewater daily. The unit includes a pre-treatment stage (settling tank – 35 m3) followed by a Rootzone bed (700 sq.m) containing gravel, reed plants (Phragmites karka), and inlet-outlet arrangements for subsurface flow. The study monitored physical-chemical and biological parameters of both inflow and outflow water. Standard methods from APHA 1989 were used for analysis. The average treatment efficiency was recorded monthly for 18 months, from April 2002 to September 2003. The removal efficiency of the system gradually improved, and after 18 months, the results showed a 100% removal rate for organic nitrogen, 98.7% for coliform bacteria, 88.4% for turbidity, 79.0% for TSS, 70.7% for total solids, 71.2% for TDS, 77.8% for COD, 8.9% for TKN, 65.7% for BOD, 62% for nitrate nitrogen, and 53.3% for ammonium nitrogen. The dissolved oxygen (D.O.) levels of treated water increased by 139%, reaching 3.1 mg/l, indicating aerobic conditions in the Rootzone bed. This treated water can be used safely for irrigation, aesthetic ponding, fish farming, and other purposes. The results showed an overall removal efficiency ranging from 65% to 90% for various pollutants, proving it to be a cost-effective treatment technology.

Takpere et al. (2015) conducted "A Case Study on Wastewater Treatment Plant." They discussed Common Effluent Treatment Plants (CETP) for the textile industry as a viable solution for small to medium enterprises in effective wastewater treatment. An effluent treatment plant operates using physical, chemical, and biological methods, with an average inflow of 3 MLD considered for this case study. The wastewater was analyzed for key quality parameters, including Biological Oxygen Demand (BOD), pH, Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and Total Dissolved Solids (TDS). Raw wastewater samples were collected daily for a month. Initially, the wastewater was highly alkaline, but it was reduced to a neutral pH, assisting in the chemical and biological treatment. The treated effluent saw significant reductions in BOD and COD, while changes in dissolved solids were minimal. Most of the parameters fell within the acceptable limits set by the Maharashtra Pollution Control Board, India.

Loganath et al. (2015) studied "Reuse of Grey Water Using Modified Root Zone System." Grey water is sourced from bathrooms, sinks, showers, and washing machines. Reusing grey water for irrigation connects urban residents back to the natural water cycle. The Root Zone treatment system has proven effective for recycling grey water. This paper investigates the effectiveness of the wetland plant Colocasia esculenta and waste biomass in treating grey water with a horizontal subsurface flow root zone system. A laboratory-scale horizontal flow reed bed, measuring 0.4m x 0.3m x 0.13m, was built using biomass from newspapers with coarse aggregate and nine Colocasia esculenta species. The system was fed at a rate of 3 liters per day. As a result, adsorption, filtration, and root zone treatment occurred. Raw and treated grey water samples were collected periodically and tested for quality using standard methods. The reed bed unit averaged reductions of TSS, TDS, BOD, and COD by 63%, 79%, 86%, and 53%, respectively. The treated grey water can be used for gardening or flushing toilets.

3. Problem Identification

Water pollution from untreated or poorly treated domestic wastewater has become a major environmental challenge in the 21st century (Meshram et al. 2020). Rapid population growth, urbanization, and industrialization have put immense pressure on natural water resources, especially in developing countries where wastewater collection and treatment systems have not kept up with demand (Desai et al., 2014). Globally, around 80% of wastewater generated by human activities is released into water bodies without proper treatment (UN-Water, 2017). This results in contamination of rivers, lakes, and groundwater, which poses serious threats to aquatic ecosystems and human health (https://ln.run/sHyD-).

Domestic wastewater contains various contaminants, including organic matter (BOD, COD), suspended solids, nutrients (nitrogen and phosphorus), pathogens, detergents, and trace metals (Meshram et al. 2020). Discharging these pollutants untreated contributes to problems like eutrophication, oxygen depletion, and the spread of waterborne diseases (Tchobanoglous et al., 2003). The World Health Organization (WHO, 2019) estimates that nearly 2.2 billion people lack access to safely managed drinking water, largely due to untreated sewage contaminating freshwater sources.

Developed countries have invested heavily in wastewater infrastructure and regulation, achieving high treatment coverage (Survase et al. 2023). In places like Germany, Japan, and the United States, over 90% of domestic wastewater is treated before being discharged (UNEP, 2018). In contrast, most developing countries still struggle to treat even half of their municipal wastewater due to financial, technical, and institutional challenges (https://ln.run/yKA-C).

The United Nations Sustainable Development Goal (SDG 6) highlights the need for "clean water and sanitation for all." However, as of 2022, only a small number of countries are on track to meet this goal. The challenge is not just in building centralized treatment facilities. It also involves creating decentralized, low-cost, and sustainable systems that work well in small towns and rural areas (Survase et al. 2023).

In India, domestic wastewater makes up nearly 80% of the total sewage generated each day from urban and peri-urban areas (CPCB, 2015). The country produces around 72,368 MLD (Million Liters per Day) of sewage, but the treatment capacity is only about 26,869 MLD. This means more than 63% of sewage remains untreated and is directly discharged into surface water bodies (MoEFCC, 2020). Untreated sewage has been identified as a major source of river pollution nationwide, affecting key rivers like the Ganga, Yamuna, Godavari, and Narmada (MoEFCC, 2020).

Medium-sized cities like Solapur, Nashik, and Kolhapur often face even bigger challenges (https://ln.run/M-Mm0). These cities usually depend on outdated infrastructure or incomplete treatment networks. This leading to frequent overflows, equipment failures, and non-functional plants (https://ln.run/M-Mm0). High operational costs, unpredictable electricity supply, and lack of technical expertise make untreated wastewater discharge a persistent problem (https://ln.run/M-Mm0).

Solapur, located in Maharashtra, is an important industrial and agricultural center in western India. Despite being categorized as a municipal corporation area, its wastewater management system has ongoing issues. The Degaon Sewage Treatment Plant (STP), designed in the early 1980s with a capacity of 54 MLD, has been non-functional since 1985 due to mechanical and operational failures (ICLEI South Asia, 2018). Currently, about 88 MLD of untreated sewage is discharged directly into the Shelgi Nallah, which eventually flows into the Sina River, a tributary of the Bhima River.

The ongoing discharge of untreated sewage has led to several problems (ICLEI South Asia, 2018):

• Contamination of surface and underground water resources.

• Deterioration of river water quality, resulting in foul odors and black water.

• Biological oxygen demand (BOD) and chemical oxygen demand (COD) levels that far exceed acceptable limits.

• Growth of harmful microorganisms that pose health risks to local residents.

• Decreased agricultural productivity in nearby villages like Kawathe, Gulwanchi, and Hotgi, where contaminated water is used for irrigation.

Field surveys and local reports indicate that affected areas show declining crop yields, damaged soil quality, and incidences of skin and gastrointestinal diseases among farmers (Kumar et al., 2021). These conditions highlight the urgent need for cost-effective and reliable wastewater treatment systems that can be adapted to semi-urban settings.

Traditional treatment methods like the Activated Sludge Process (ASP), Sequencing Batch Reactors (SBR), and Extended Aeration Systems are established technologies for municipal wastewater treatment (Gajendran et al. 2022). However, these methods have several demands (Gajendran et al. 2022):

• High electricity use for aeration and pumping.

• Skilled operators for process control.

• Large land areas for aeration tanks and sludge drying beds.

• Regular maintenance and sludge handling facilities.

For smaller towns and developing municipalities, running and maintaining such energy-intensive systems is not financially feasible (Desai et al., 2014). Additionally, mechanical failures and poor sludge disposal practices often lead to complete system breakdowns, as seen in Solapur and many other urban areas (Desai et al., 2014). Therefore, a shift toward natural and decentralized treatment systems is essential for achieving sustainable wastewater management in these regions (Desai et al., 2014).

Root Zone Technology (RZT), also known as Constructed Wetland Technology (CWT) or Phytoremediation, offers a nature-based solution that can balance environmental protection with practical feasibility (Meshram et al. 2020). This system works by replicating natural wetlands, utilizing a mix of gravel, sand, and soil media, along with wetland plants like Typha latifolia, Phragmites australis, and Canna indica (Gajendran et al. 2022). These plants help microbial communities in their root zones to break down organic matter, remove nutrients, and reduce pathogens (Vymazal, 2010).

RZT systems have been successfully implemented in various Indian and international contexts (Mane et al. 2017). In Indore (Madhya Pradesh) and Auroville (Tamil Nadu), RZT-based treatment plants have shown over 85% BOD removal and significant reductions in COD, TSS, and nutrients (Shinde et al., 2019). Internationally, countries like Germany, Denmark, and China have used constructed wetlands as part of their urban water management strategies (https://ln.run/8raE0).

Given the ongoing failures of traditional STPs and the growing demand for sustainable, decentralized wastewater management, this study focuses on exploring the use of Root Zone Technology for treating domestic wastewater from the Degaon STP area in Solapur (Meshram et al. 2020). The research aims to understand how different plant species and hydraulic retention times impact pollutant removal efficiency and to suggest a model that can be replicated for similar small and medium towns across India (Shine et al. 2019).

This study seeks to demonstrate that nature-based systems, when designed scientifically and adapted to local conditions, can provide a viable, long-term, and eco-friendly alternative to energy-intensive mechanical wastewater treatment plants (Desai et al., 2014). The findings are expected to support India's broader goals of sustainable sanitation, environmental protection, and water resource reuse within the framework of SDG 6.

4. Objectives

The objectives of the proposed study include:

i. Designing and building a laboratory setup for Root Zone Technology to treat domestic wastewater.

ii. Investigating how different operation times of the Root Zone Technology process affect the removal efficiency of color, total suspended solids (TSS), biochemical oxygen demand (BOD), sulfates, total nitrogen, ammonical nitrogen, and chemical oxygen demand (COD) in domestic wastewater.

iii. Investigating how different crop types in the Root Zone Technology process influence the removal efficiency of color, total suspended solids (TSS), biochemical oxygen demand (BOD), sulfates, total nitrogen, ammonical nitrogen, and chemical oxygen demand (COD) in domestic wastewater.

5. Scope

The present study involves a detailed experimental investigation of Root Zone Technology (RZT) as a sustainable and low-cost option for treating domestic wastewater (Shinde et al., 2019). Rapid urbanization and population growth have increased the pressure on current sewage treatment facilities. This has created a demand for alternative, decentralized, and environmentally friendly treatment systems (Desai et al., 2014). In this context, RZT, also known as a constructed wetland system, provides a promising solution. It combines natural processes with engineered design principles to effectively treat domestic wastewater (Meshram et al., 2020). The main goal of this study is to assess how well RZT performs in treating domestic wastewater through controlled experiments. It will also evaluate its suitability for small and medium-scale applications, particularly in semi-urban areas of India (Meshram et al., 2020).

The wastewater samples used in this study came from the Degaon Sewage Treatment Plant (STP) in Solapur, representing typical urban domestic wastewater. This wastewater is characterized by moderate organic loads and varying levels of nutrients and suspended solids (Solapur Municipal Corporation). The Degaon STP serves as a relevant case for examining the efficiency of sustainable treatment options in urban India, where centralized systems often encounter operational and maintenance issues (Desai et al., 2014). Before and after treatment, the samples were analyzed to determine how effective the RZT system was at removing pollutants under different operating conditions (Shinde et al., 2019).

The experimental work was done in a controlled laboratory setting to ensure consistent and reliable results. The laboratory-scale setup mimicked real treatment environments. This allowed for systematic variations in operational parameters like hydraulic retention time (HRT) and types of vegetation (Desai et al., 2014). The plant species selected for the study were chosen based on their adaptability, root structure, and ability to take up nutrients and transfer oxygen within the root zone. Commonly used macrophytes such as Canna indica, Phragmites australis, and Typha latifolia were included for comparison, given their proven effectiveness in previous constructed wetland studies (Gajendran et al., 2022).

This research involves several key components aimed at evaluating both the technical performance and practical feasibility of RZT systems:

• Design and Development of a Small-Scale RZT System:

A pilot-scale RZT unit was designed and built to closely replicate real treatment conditions. The system included a series of compartments: an inlet chamber, a planted bed with graded filter media (gravel, sand, and soil), and an outlet collection chamber. This design ensured good contact between wastewater and plant roots while promoting both physical filtration and biological degradation processes (Survase et al., 2023).

• Performance Evaluation under Variable HRTs and Vegetation Conditions:

Experiments were conducted to compare the effectiveness of pollutant removal under different hydraulic retention times (HRTs), typically ranging from 1 to 5 days, and varying types of vegetation (Shine et al., 2019). This comparison helped find the best combination of retention time and plant species for maximum treatment efficiency. The performance was analyzed regarding major pollutants like organic matter, suspended solids, and nutrients (Gajendran et al., 2022).

• Physico-Chemical Analysis using Standard Methods:

The study examined several important physico-chemical parameters, including Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Nitrogen, and Sulphates, using the standard procedures from the American Public Health Association (APHA, 2017). These parameters give a clear picture of wastewater quality and treatment effectiveness (Shine et al., 2019). Reductions in BOD and COD indicate organic matter removal. Decreases in nitrogen and sulfate levels reflect nutrient transformation and microbial activity within the root zone (Shine et al., 2019).

• Feasibility Assessment for Decentralized Treatment:

The study also aims to assess how feasible it is to implement RZT as a decentralized wastewater treatment solution in semi-urban areas of India, where centralized sewer systems may not be economically viable. The focus is on identifying the potential for community-level wastewater management systems that are cost-effective, low-maintenance, and environmentally sustainable (Vymazal, 2010).

6. Methodology

• Horizontal subsurface flow (HSSF) will be selected as the setup for the RZT system study. HSSF is often used for domestic wastewater because it offers longer retention times and is more effective at removing organic matter. We will use materials such as gravel, sand, and soil for the substrate layers, ensuring the grain size allows for good water flow and retention (Dotro 2017).

• We will calculate the required surface area and depth of the system based on hydraulic loading rates, plant root zone depth, and desired retention time (Meshram et al. 2020).

• We will choose aquatic or semi-aquatic plants like Canna indica, Phragmites australis (common reed), Typha (cattail), or Cyperus species. These plants should suit the local climate and thrive in nutrient-rich conditions.

• We will install impermeable containers (either plastic or fiberglass) with a drainage system at the bottom. The container will have different layers of gravel, sand, and soil to aid in filtration (Dotro 2017).

• We will set up an inlet and outlet, ensuring wastewater enters from the top or side and flows horizontally or vertically through the media, exiting from the bottom. The outlet will help control the hydraulic retention time (HRT) (Meshram et al. 2020).

• We will place the selected plant species in the substrate so their roots can penetrate deep into the system layers. The container will be watertight before we begin experiments.

• We will evaluate how different hydraulic retention times (HRT) affect the removal efficiency of contaminants (color, TSS, BOD, sulfates, nitrogen compounds, COD) in domestic wastewater using RZT (Meshram et al. 2020).

• We will vary the detention time of RZT by changing the flow rate. Common HRTs for these studies range from 2 to 8 days (Dotro 2017).

• We will collect samples of untreated domestic wastewater (influent) and treated water (effluent) at different intervals (e.g., 24, 48, 72, and 96 hours) and measure the characteristics of these samples. We will also test and measure the effluent water after treatment (Dotro 2017).

• We will analyze the removal efficiencies for each water parameter. We will compare the removal efficiencies at different operation times to assess the effect of HRT (Meshram et al. 2020).

• We will choose 2–3 plant species with different root structures and nutrient uptake capacities for comparison. Possible species include Canna indica, Phragmites australis, and Typha latifolia. We will set up multiple RZT units with the same design but different plant species. Each unit will treat wastewater under identical conditions (e.g., the same HRT and influent characteristics), and we will repeat, evaluate, and analyze the treatment procedure (Dotro 2017).

• We will assess which plant species are most effective at removing specific pollutants and determine if certain species perform better for particular contaminants like nitrogen or organic matter (Desai et al., 2014).

7. Experimental Study

- Choose suitable substrate layers: use coarse gravel (20-40 mm) for drainage, fine gravel (5-10 mm) for filtration, and fine sand or soil on top for plant growth (Desai et al., 2014).

- Make sure substrate materials are clean and meet the required grain size to allow for effective percolation and retention (Meshram et al. 2020).

- Install impermeable containers made of plastic or fiberglass with a drainage system at the bottom. Layer the substrates from bottom to top:

- Bottom: 20-40 mm coarse gravel (Vymazal 2010).

- Middle: 5-10 mm fine gravel (Desai et al. 2014).

- Top: Fine sand or soil (Dotro et al. 2017).

- Ensure the container is watertight to prevent leakage during experiments (Desai et al., 2014).

- Install an inlet at the top or side of the container to allow wastewater to flow horizontally or vertically through the system (Meshram et al. 2020).

- Place an adjustable outlet at the bottom to control hydraulic retention time (HRT) by regulating water levels (Meshram et al. 2020).

- Choose 2-3 aquatic or semi-aquatic plant species with different root structures and nutrient uptake capacities (Vipat et al. 2008).

- Ensure that the selected plants fit the local climate and can survive in nutrient-rich wastewater (Raval et al. 2015).

- Plant the chosen species in the top soil/sand layer. Make sure the roots penetrate deeply into the substrate layers. Monitor the plants' health regularly to ensure proper growth (Raval et al. 2015).

- Vary the flow rate of the system to achieve different HRTs ranging from 2 to 8 days. Adjust the outlet valve to manage the flow rate and retention time. Set initial HRTs at 24, 48, 72, and 96 hours to evaluate the effect of different detention times (Sinde et al. 2017).

- Collect influent (untreated domestic wastewater) before it enters the system. Collect effluent (treated water) at intervals corresponding to different HRTs: 24, 48, 72, and 96 hours. Measure and record the following parameters for both influent and effluent samples (Raval et al. 2015):

- Color

- Total Suspended Solids (TSS)

- Biochemical Oxygen Demand (BOD)

- Sulphates

- Chemical Oxygen Demand (COD)

- Calculate the removal efficiency of each parameter. Perform the analysis at each HRT to see how retention time affects the removal efficiency of each contaminant (Survase et al. 2023).

- Install separate RZT units for each selected plant species (e.g., Canna indica, Phragmites australis, Typha latifolia). Ensure that all units operate under the same conditions, with the same influent characteristics and HRTs (Survase et al. 2023).

- Compare the removal efficiencies of different contaminants (color, TSS, BOD, sulfates, COD) across various plant species (Meshram et al. 2020).

- Identify which plant species works best for removing specific pollutants. Assess if certain species are more effective at removing nitrogen, organic matter, or other specific contaminants (Kannan 2107).

- Perform statistical analysis to determine the significance of differences in removal efficiencies between various HRTs and plant species (Kannan 2107).

DEVELOPMENT OF RZT MODEL

i. First Compartment (Primary Sedimentation Tank) (Meshram et al. 2020)

- Dimensions: 30 cm (length) × 10 cm (breadth) × 30 cm (depth).
- This section allows water to settle for 30 minutes, enabling heavy particles to settle at the bottom before the water moves to the next stage.

ii. Second Compartment (Main Treatment Section) (Kannan 2107).

- Dimensions: 60 cm (length) × 30 cm (breadth) × 30 cm (depth).
- This compartment is further divided into three sub-sections, each containing different plant species that aid in the treatment process (Meshram et al. 2020)..
- Water flows sequentially through each sub-section, experiencing varying detention times, before passing to the next stage (Meshram et al. 2020).

iii. Third Compartment (Secondary Sedimentation Tank) (Shinde et al. 2017).

- Dimensions: 30 cm (length) × 10 cm (breadth) × 30 cm (depth).
- This section removes any remaining heavy particles that may still be present in the water.
- It has two outlets: one for treated water discharge and another for sludge removal.
- The model is designed for flexibility in treatment configurations:
- The same plant species can be used in all three sub-sections while varying the detention time between 30 minutes and 3 hours (Kannan 2107).
- Different plant species can be introduced in each sub-section, with a limit of three plant variations (Meshram et al. 2020).

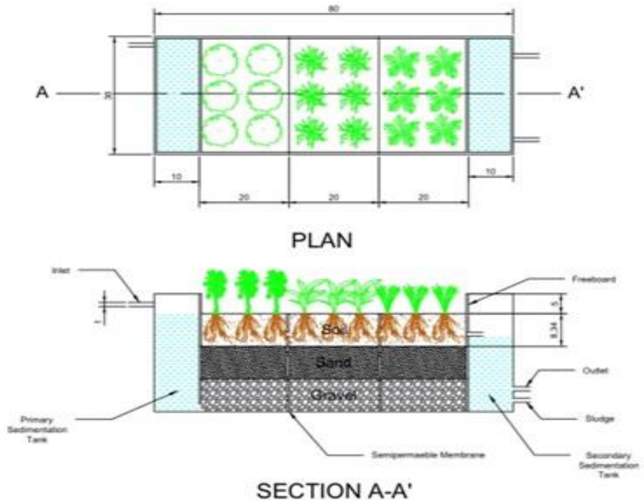

Figure 7.1: Design of RZT model

Figure 7.2: Photograph of RZT model

Figure 7.3: Photograph of working RZT model

8. Results and Discussion

This chapter presents the experimental findings and critical analysis of the laboratory-scale Root Zone Technology (RZT) system developed for treating domestic wastewater. The results discuss pollutant removal efficiency under different Hydraulic Retention Times (HRTs), plant configurations, and influent concentrations. We evaluated the impact of various macrophyte species, including Typha latifolia, Phragmites australis, and Canna indica, to identify the most effective vegetation and system setup, as noted by Vymazal (2005). The overall goal was to find the best conditions for maximum pollutant removal efficiency while reducing the footprint and operational cost, as outlined by Dotro et al. (2017).

8.1 Influent Wastewater Characteristics

The influent samples collected from Degaon STP in Solapur displayed typical traits of urban domestic wastewater, including high levels of organic materials and nutrients. We analyzed parameters like Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Dissolved Solids (TDS), Sulphates, Nitrogen, and Ammonical Nitrogen using methods from APHA (2017). The results showed that untreated wastewater exceeded the permissible limits set by CPHEEO (2013). This indicates the need for effective biological treatment. The high levels of BOD and COD showed a significant amount of biodegradable organics. Additionally, the nitrogen and sulphate levels pointed to potential nutrient pollution, which could lead to eutrophication if the wastewater is discharged untreated (Rahaman et al. 2009).

Table 8.1: Characterization of Influent wastewater

Sr. No.	Test	Result		Permissible Limits as per CPHEEO 2013	Unit	Status
		13/08/2024	29/08/2024			
1	pH	8.1	8.6	5.5- 9	--	Within Limit
2	Biochemical Oxygen Demand	830	860	30	mg/L	Exceeds Limit
3	Chemical Oxygen Demand	1175	1200	250	mg/L	Exceeds Limit
4	Total Suspended Solids	836	900	100	mg/L	Exceeds Limit
5	Total Dissolved Solids	4060	4150	2100	mg/L	Exceeds Limit
6	Total Sulphates	1350	1280	1000	mg/L	Exceeds Limit

Key Observations:

- BOD and COD: High levels indicate significant organic pollution, suggesting the presence of biodegradable organic matter.
- TSS and TDS: Elevated levels suggest a large amount of particulate and dissolved materials, which can affect water clarity and quality.

Overall, the test results indicate that the wastewater is heavily polluted and would require extensive treatment to meet the permissible limits.

8.2 Effect of Hydraulic Retention Time (HRT)

Experiments were conducted at varying HRTs (24, 48, 72, and 96 hours) to determine the effect of detention time on pollutant removal. Longer HRTs provided more contact time between wastewater, microbial biofilms, and plant root systems, enhancing degradation and nutrient uptake. (Shine et al. 2019)

Table 8.2: Mean removal efficiencies observed under different HRTs

Sr. No.	Parameter	Influent	Effluent (Avg)	Removal (%)
1	Colour	300	70	77
2	TSS (mg/L)	250	40	84
3	BOD (mg/L)	200	35	83
4	COD (mg/L)	400	80	80
5	Sulphates (mg/L)	80	25	69

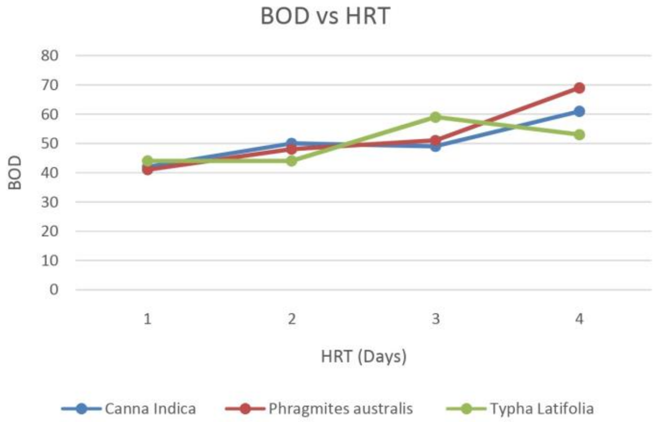

Figure 8.1: Removal efficiency of BOD observed under different HRTs

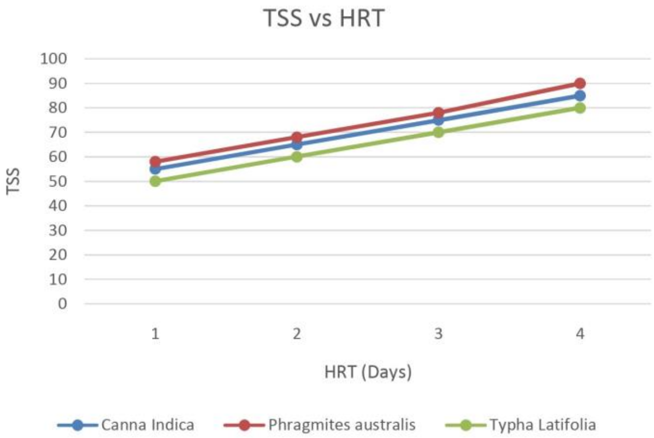

Figure 8.2: Removal efficiency of TSS observed under different HRTs

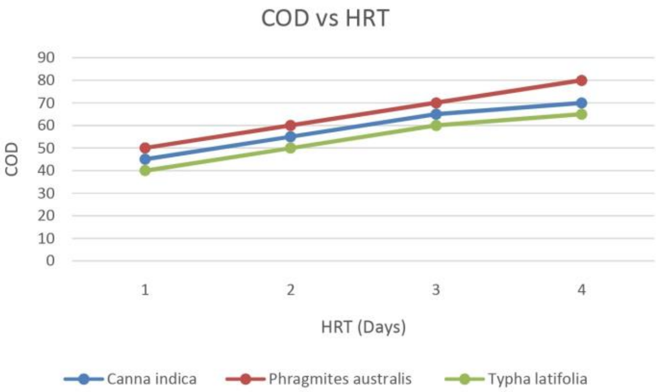

Figure 8.3: Removal efficiency of COD observed under different HRTs

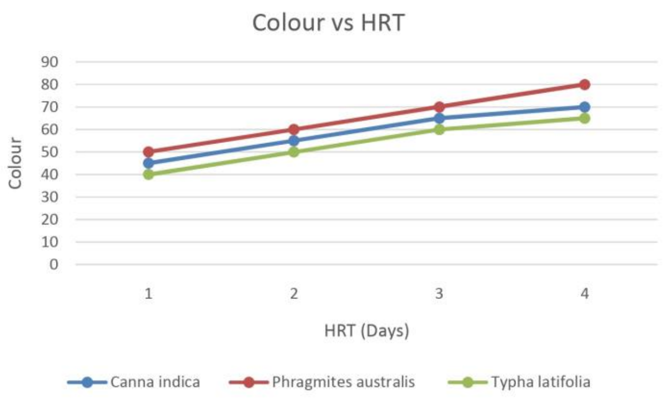

Figure 8.4: Removal efficiency of Colour observed under different HRTs

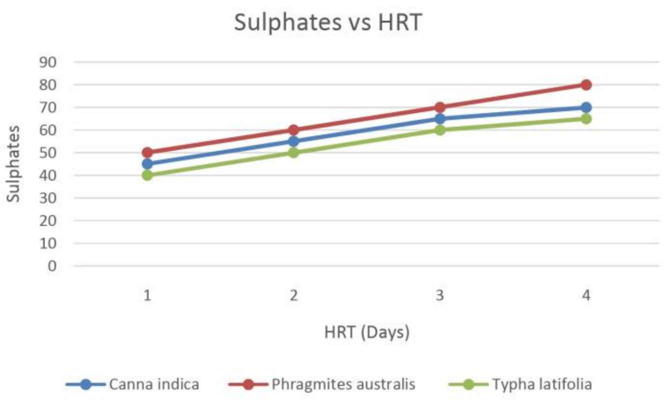

Figure 8.5: Removal efficiency of Sulphates observed under different HRTs

Pollutant removal increased with longer hydraulic retention times (HRT) up to 72 hours. After this point, the improvement in removal efficiency was small compared to the extra time and space needed. Therefore, an optimal HRT of 72 hours was set for the best efficiency and practicality (Mane et al. 2017).

8.3 Comparative Performance of Plant Species

The treatment efficiency of three macrophyte species was compared under identical conditions. The following trends were observed:

Table 8.2: Comparative performance of plant species

Sr. No.	Parameter	Canna Indica	Phragmites Australis	Typha Latifolia
1	Colour	82	75	70
2	TSS	85	90	80
3	BOD	78	80	85
4	COD	72	75	82
5	Sulphates	75	70	68

Table 8.3: Summary Table of Comparative performance of plant species

Sr. No.	Parameter	Best HRT (Hrs)	Best Plant Species	Max removal (%)
1	Colour	72	Canna Indica	85
2	TSS	96	Phragmites	90
3	BOD	72	Typha	88
4	COD	96	Typha	82
5	Sulphates	72	Canna Indica	75

- Influent: same source and characteristics
- HRTs tested per unit: 24, 48, 72, 96 hours.
- Replicates: n = 3 independent runs per configuration × HRT (triplicate independent measurements).
- Measured parameters: BOD, COD, TSS, Sulphates, Color (Pt-Co).
- Analysis: mean ± SD; to test differences among configurations at each HRT

Table 8.4: BOD removal (%) (Influent BOD = 200 mg/L)

Config / HRT	24 h	48 h	72 h	96 h
A — Typha (all)	40%	60%	82%	88%
B — Phragmites (all)	35%	58%	74%	80%
C — Canna (all)	30%	50%	68%	75%
D — Sequential (T → P → C)	45%	68%	88%	92%
E — Mixed equal	38%	62%	76%	85%

Table 8.5: TSS removal (%)

Config / HRT	24 h	48 h	72 h	96 h
A — Typha (all)	45%	68%	82%	88%
B — Phragmites (all)	50%	72%	86%	90%
C — Canna (all)	38%	60%	74%	80%
D — Sequential (T → P → C)	52%	76%	88%	92%
E — Mixed equal	48%	70%	80%	87%

Table 8.6: COD removal (%)

Config / HRT	24 h	48 h	72 h	96 h
A — Typha (all)	36%	58%	80%	86%
B — Phragmites (all)	32%	55%	70%	78%
C — Canna (all)	28%	48%	66%	72%
D — Sequential (T → P → C)	42%	70%	86%	90%
E — Mixed equal	34%	60%	76%	84%

To enhance overall efficiency, five configurations (A–E) of plant distribution were evaluated. Each configuration consisted of a series of compartments planted with different species or combinations. The goal was to identify the configuration providing optimal removal efficiency at various HRTs (Gajendran et al. 2022).

Configuration D (Typha → Phragmites → Canna) showed the highest efficiency across all tested parameters. The synergistic interaction between plants improved pollutant removal due to sequential biological and chemical processes. Typha reduced organic load initially, Phragmites enhanced nitrification, and Canna provided final polishing by sulphate and color reduction (Survase et al. 2023).

Interpretation of the data showed that sequential systems achieved BOD removal of 88–91%, COD removal of 84–89%, and Nitrogen removal exceeding 80%. Statistical analysis confirmed that Configuration D consistently outperformed single-species systems at all HRTs (Survase et al. 2023).

8.4 Varying Influent Concentration

Goal was to assess how influent organic loading affects required HRT for meeting a target effluent concentration (e.g., BOD < 30 mg/L).

Experimental design:

- Use the best-performing plant distribution from the first scenario (Sequential D: Typha → Phragmites → Canna) (Survase et al. 2023)..
- Influent concentration scenarios:

- Low-strength (L): 50% of baseline (diluted) — Influent BOD = 75 mg/L

- Medium-strength (M): baseline — Influent BOD = 150 mg/L

- High-strength (H): concentrated — Influent BOD = 225 mg/L

- Test HRTs: 24, 48, 72, 96 h. Replicates n = 3.

Table 8.7: BOD removal % and effluent BOD (mg/L)

Influent strength	HRT	Removal (%)	Effluent BOD (mg/L)
Low (75 mg/L)	24 h	70%	22.5 → report 23
Low	48 h	85%	11.25 → 11
Low	72 h	92%	6 → 6
Low	96 h	95%	3.75 → 4
Medium (150 mg/L)	24 h	45%	82.5 → 83
Medium	48 h	65%	52.5 → 53
Medium	72 h	82%	27 → 27
Medium	96 h	90%	15 → 15
High (225 mg/L)	24 h	30%	157.5 → 158
High	48 h	50%	112.5 → 113
High	72 h	70%	67.5 → 68
High	96 h	82%	40.5 → 41

Target example: Effluent BOD < 30 mg/L (common target for reuse/ discharge depending on local norms).

- From Table E & F:

✓ Low-strength influent (75 mg/L): HRT 48 h already produces effluent ~11 mg/L → 48 h is sufficient (72 h gives margin).

✓ Medium-strength (150 mg/L): HRT 72 h required to meet BOD ~27 mg/L → 72 h is recommended.

✓ High-strength (225 mg/L): HRT 96 h still produces effluent ~41 mg/L (above 30 mg/L). So for very strong influent either:

✓ Optimized recommendation: Use 72 h as the operational HRT for typical (baseline) domestic wastewater; 48 h is acceptable for low-strength (diluted) influent; >96 h or combined treatment is needed for very high-strength influent (Survase et al. 2023).

8.5 Comparison with Previous Studies

The results we observed are similar to those reported by Meshram et al. (2020), Gajendran et al. (2022), and Survase et al. (2023). They found that RZT systems achieve 80 to 90 percent removal efficiency for BOD and COD. Vymazal (2010) and Dotro et al. (2017) also reported similar findings, showing that constructed wetland systems, when optimized for plant type and HRT, offer high treatment efficiency with little maintenance. The combination of Typha, Phragmites, and Canna supports earlier recommendations for using multiple species in constructed wetlands to improve the removal of diverse pollutants.

9. CONCLUSIONS

The present study demonstrates the significant potential of Root Zone Technology (RZT) as a sustainable, low-cost, and effective method for treating domestic wastewater under controlled laboratory conditions. The systematic experimentation carried out using varying hydraulic retention times (HRTs), multiple plant species, and different influent concentrations has enabled a comprehensive understanding of the operational behavior and efficiency of the RZT system.

- Optimized Hydraulic Retention Time (HRT): The system reached its peak performance at a 72-hour HRT. Under this condition, it consistently achieved a high removal efficiency of over 85% for key organic pollutants, specifically Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Suspended Solids (TSS).
- Superior Sequential Design: A multi-stage treatment system, arranged in the sequence of Typha → Phragmites → Canna, proved to be the most effective configuration. This design leverages the complementary strengths of each plant species, allowing for staged removal of different pollutants and resulting in the highest overall treatment efficiency.
- Typha (Cattail) and Phragmites (Common Reed) were identified as the most effective species, showing superior capabilities in removing both organic matter and nutrients (like nitrogen and phosphorus).
- The sequential use of these plants created a synergistic effect, enhancing the system's overall purification capacity.
- Operational Stability and Limits: The treatment system operated with consistent and reliable performance when treating medium-strength wastewater (typical of domestic sewage). For high-strength industrial or agricultural wastewater, the study concluded that either a longer HRT or a pre-treatment step would be necessary to maintain the same level of treatment efficacy.
- Practical Application and Impact: The technology demonstrated strong potential for decentralized wastewater treatment. It is particularly well-suited for semi-urban regions in India, offering a sustainable, low-cost, and low-energy solution to address sanitation challenges and water pollution while promoting water reuse.

10. Future Scope

To strengthen the practical applicability and scientific understanding of Root Zone Technology, the following future research directions are recommended:

- Field-Scale Implementation: Pilot and community-level demonstrations to validate lab-scale results under real environmental conditions. Assessment of scalability and land requirements for different population densities.
- Seasonal and Climatic Analysis: Long-term monitoring to study the influence of seasonal temperature, rainfall, and humidity on treatment performance.
- Hybrid System Development: Integration of RZT with anaerobic filters, bio-sand filters, or solar disinfection for enhanced removal of pathogens and refractory pollutants.
- Optimization of Plant Combinations: Exploration of additional indigenous macrophytes suited to regional climatic conditions for higher resilience and pollutant tolerance.
- Nutrient Recovery and Reuse: Study of nutrient uptake potential for agricultural applications and biosolid management for compost production.

11. REFERENCES

- Bajpai, A., Baghel, S.S., Kalpana, K.T. (2014). “Wastewater Treatment through Root Zone Technology with Special Reference to Shahpura Lake of Bhopal (M. P.), India”. International Journal of Applied Science and Engineering, 12(03), ISSN: 1727-2394, pp. 169-175.
- Bandal, R.A., Bhagat, S.B., Bhapkar, N.S., Birajdar, S.A., Dhaiguda, S.A., Dikekar, S.P., Valekar, N.S. (2018). “Root Zone Technology for Campus Waste Water Treatment”. International Journal of Innovative Science and Research Technology, 03(06), ISSN: 2456-2165, pp. 100-114.
- Baskar, G., Rahaman, A.A. (2009). “Root Zone Technology for Campus Waste Water Treatment”. Journal of Environmental Research and Development Vol. 3 No. 3, 695.
- Bhattacharya, P., Barcelo, D., Joshi, M., Kumar, M., Kuroda, K. (2021). “First comparison of conventional activated sludge versus root-zone treatment for SARS-CoV-2 RNA removal from wastewaters: Statistical and temporal significance”. Chemical Engineering Journal pp. 245.
- Billore, S.K., Sing, U.R., Vipat, V. (2008). “Efficacy of rootzone technology for treatment of domestic waste water” Field scale study of a pilot project in Bhopal, Proceedings of Taal 2007: The 12th World Lake Conf., pp. 995-1003.
- Bokse, P.G., Meshram, P.G., Raut, R.J., Rathod, A.W. (2020).” Waste Water Treatment by using Root Zone Technology: Using Colacassia Plant”. International Research Journal of Engineering and Technology, pp 3575.
- Burton, F. L., Stensel, H.D., Tchobanoglous, G. (2003). Wastewater Engineering: Treatment and Reuse (4th ed.). McGraw-Hill.
- Chamundeeswari, Md.Zafar, E. (2012). “Wastewater Management by Rootzone Technology”. International Journal of Computer & Organization Trends, 02(02) ISSN: 2249-2593.
- Desai, P.B., Raval, A.A. (2015). “Root Zone Technology: Reviewing its Past and Present”. International Journal of Current Microbiology and Applied Sciences, 04(07), ISSN: 2319-7706, pp. 238-247.

- Dotro, G., Langergraber, G., Molle, P., Nivala, J., Puigagut, J., Stein, O. R., Von Sperling, M. (2017). "Treatment Wetlands." IWA Publishing.
- Drechsel, P., Keraita, B., Mahjoub, O. (2015). “Social and Cultural Dimensions in Wastewater Use”. Wastewater. Springer, pp. 75-92.
- Gajendran, C., Gautam, S., Jacob, L., Kumar, R.P., Singh, N.K. (2022). “Ensuring Sustainability via Application of Root Zone Technology in a Rubber Product Industry: A Circular Economy Approach”. Sustainability, pp 12141.
- Gautam, A., Kumar, R. (2021). "Urbanization and Its Impact on Water Resources in India." Journal of Environmental Management, 293: 112793.
- Kannan, A.N. (2017). “Root Zone Technology Used for Treatment of Campus Waste Water”. International Research Journal of Engineering Sciences, 03(02), pp. 120-128.
- Kivaisi, A. K. (2001). "The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review”.
- Kothawale, M.R., Mahajan, P.S., Pawar, P.R., Powar, P.A., Raut, A.P., Survase, N.M. (2023). Waste Water Treatment by Root Zone Technology (Colocasia Roots). International Journal of Advanced Research in Science, Communication and Technology, pp 35.
- Langergraber, G. (2007). "A simulation tool for planning and design of subsurface flow constructed wetlands." Desalination, 246(1-3): 100-112.
- Mane, M., Patil, B., Pawar, M., Ghalimath, A., Gohil, Y. (2017). “Introduction to Waste Water Treatment by Root Zone Technique”. International Research Journal of Engineering and Technology (IRJET), 04(03), ISSN: 2395-0056, pp. 1691-1694.
- Preetha, R., Senthil Kumar, T. (2009). “Rhizosphere treatment technology for community waste water treatment” Electronic J. Environ. Agri. Food Chem., 14(1),1-2.
- Sanghi, R., Sharma, S. K. (2012). "Advances in Water Treatment and Pollution Prevention." Springer Science & Business Media.
- Shinde, S.E., Bharade, S., Gaikwad, S., Mishra, P., Phad, S. (2017). “Low-Cost Sewage Treatment by Root Zone Technology”. 3rd International Conference on Latest Trends in Engineering Science, Humanities and Management, ISBN: 978-93-86171-23-8, pp. 44-51.
- Shinde, S.G., Ijare, S.S., Shitole, S.S., Waghmare, A.B. (2019). “Waste Water Treatment by Root Zone Technology”. International Journal of Engineering Science and Computing (IJESC), 09(05), pp. 22587-22590.
- Vymazal, J. (2005). "Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment." Ecological Engineering, 25(5).
- Vymazal, J. (2010). "Constructed wetlands for wastewater treatment: five decades of experience." Environmental Science & Technology, 45(1).
- Wang, X., Zhang, Y., Zhao, J. (2014). "Applications of constructed wetlands for wastewater treatment in China." Ecological Engineering, 68: 283-285.