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Decentralized Wastewater Treatment Enhancing Sustainability in Rural Communities

Kathiresan Subramanian[a,b]*, Kagne Suresh[b]

[a]Hospira Healthcare Pvt. Ltd., Chennai (TN), 600017, Tamil Nadu, India
[b]Badrinarayan Barwale Mahavidhyalaya, Jalna 431213, Maharashtra, India
kathirsubramn@gmail.com

The administration of rural effluent is essential due to the scarcity of resources and infrastructure, which exacerbates health hazards and environmental degradation. Decentralised wastewater treatment (DWT) is a system that reduces the transportation costs and environmental impact by recycling wastewater for agricultural and other purposes. This study suggests a single system DWT technique that integrates natural and artificial systems to enhance rural sustainability. The system employs an Anaerobic Baffled Reactor (ABR) for the initial decomposition of organic matter, a solar-powered disinfection device, and constructed wetlands (CW) for the secondary treatment and nutrient removal. The system is cost-effective and simple to deploy by utilizing renewable energy and local components. The system satisfied local environmental criteria by reducing biochemical oxygen demand (BOD) by 85 %, total suspended solids (TSS) by 90 %, and infections by 99.9 %, as demonstrated by a pilot study conducted in a rural community. Users and administrators were impressed by the system's simplicity and ease of maintenance. Sustainability and ownership were enhanced through community involvement in design and execution. The results indicate that this DWT technique, considered a scalable and adaptive wastewater management solution, has the potential to enhance the quality of water and the health of rural environments. To enhance the sustainability and effectiveness of the system, future research will expand the number of system components and examine alternative applications, such as nitrogen recovery and greywater recycling. This study demonstrates that rural communities may address wastewater treatment challenges by employing a decentralized approach that capitalizes on community engagement and local resources. This strategy also has a positive impact on public health and the environment over time.

1. Introduction

Wastewater management is a challenge in several rural villages across the globe. This is frequently the result of a lack of funds, technical expertise, or centralized treatment facilities (Jones et al., 2021). In rural areas, conventional wastewater management procedures may not be feasible or sufficient, leading to minimal or no wastewater remediation (Larsen et al., 2015). To optimize treatment efficacy, a multistage Anaerobic Baffled Reactor (ABR) is implemented. The system's UV-based disinfection is powered by solar energy and effectively reduces pathogens while utilizing sustainable energy sources. Ecosystems are destroyed and human health is jeopardized by water and agricultural pollution. To resolve these challenges, it is imperative that we devise innovative, sustainable solutions that are tailored to the requirements of rural communities. Decentralized wastewater treatment (DWT) is a method that processes effluent at the source, rather than centrally. This approach diminishes the necessity of large-scale treatment facilities and sewerage networks in rural areas, which are not always feasible due to logistical and budgetary constraints (Zib et al., 2021). Due to its adaptability and scalability, the DWT system can treat effluent from numerous rural settlements. Decentralized systems may be customized to accommodate local resources and circumstances by enhancing their resilience and sustainability (Tian et al., 2020). A distinctive single-method DWT technique is comprised of anaerobic baffled reactors, constructed wetlands (CWs), and solar-powered disinfection devices (Casella et al., 2023). Anaerobic Baffled Reactors (ABRs) are capable of degrading organic materials, reducing the biochemical oxygen demand (BOD), and removing total suspended solids (TSS) (Hassan et al., 2023). This low-energy method is optimal for rural areas that lack infrastructure power. For instance, Sedlak et al. (2023) reported that after partially treating

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the effluent, the artificial wetlands capture it and utilize natural processes to treat it. The wetlands simulate natural ecosystems by filtering water pollutants and excess nutrients using native plant and microbial populations. The environment and biodiversity are cbenefited by the enhancement of effluent quality and habitat development. A solar-powered disinfection system is implemented to guarantee the reprocessing of water and the elimination of pathogens. Solar energy reduces operating expenses and dependence on non-renewable energy, thereby facilitating the attainment of sustainability objectives. A treatment system that satisfies the effluent treatment requirements of rural areas is established by integrating these three components. The system was designed with a focus on minimal costs, simple installation, and maintenance (Keller et al., 2023). A reduction in upfront and recurring costs may be achieved by employing sediment, sand, and local flora. The system's longevity is guaranteed by its dependability and usability, rendering it appropriate for remote regions with limited technological literacy. The system's long-term viability and the development of neighbourhood communities are contingent upon community participation. Local stakeholders and citizens cultivate a sense of dedication and accountability for the system's operation by engaging in design, construction, and maintenance (Rabaey et al., 2020). This decentralized strategy has been demonstrated to be effective in numerous rural areas through pilot studies. After treatment, the effluent no longer satisfies the local environmental regulations for pathogens, TSS, and biochemical oxygen demand. The results indicate that this distinctive DWT approach has the potential to enhance public health, water quality, and distant area development. The innovative single-method approach to decentralized wastewater treatment has the potential to address issues in rural areas (Howard et al., 2021). Types of solid waste and its management for sustainability are integral to this approach. Effective solid waste management practices include segregation at source, composting of organic waste, recycling of reusable materials, and safe disposal of hazardous waste. Conservation of water from domestic use, industrial use, and wastewater treatment also plays a crucial role in this system. Feasible methods to protect the environment from land dumping, hazardous waste drainage onto ground, river banks, and efficient handling of domestic waste (sewage) and effluent treatment processes to minimize discharge onto the ground are emphasized. The system aims for zero discharge, ensuring no impact on plants and other soil flora. Solid waste management is also a significant discussion point, including drinking and other potable water usages. The first stage after sludge collection is storing it in a sludge holding tank, which usually holds one day's worth of sludge. Larger plants may store only half a day's production. Dewatering equipment, such as filter press systems or decanter centrifuges, reduces the sludge's liquid volume. Several types of filter press system compresses dewater sludge into cakes with around 20 % solids content, and mixed with high-carbon materials like sawdust and composted aerobically.

2. Proposed Work

2.1 System Design and Overview

ABRs, CWs, and solar-powered disinfection units are essential for rural decentralized wastewater treatment systems. The objective of this method is to treat effluent locally in a sustainable, comprehensive, and effective manner by utilizing renewable energy and natural processes. The ABR, which is the fundamental treatment element, serves as the launching point. Anaerobic digestion may commence with the effluent from the ABR. Anaerobic microorganisms decompose organic materials, resulting in a substantial reduction in biochemical oxygen demand (BOD) and total dispersed particulates. The ABR's numerous sections enhance digestion by prolonging effluent interaction with microbial communities. ABR treatment diverts partially cleansed wastewater to the Constructed Wetlands (CW). The CW replicates the water filtration and refuse disposal processes of natural wetlands. They are small basins that are adorned with natural flora and are covered in sediment and debris. Physical, chemical, and biological reactions transpire as the effluent gradually traverses the marsh. The assimilation of nutrients, including nitrogen and phosphorus, the decomposition of pollutants, and the collection of dispersed particles are all dependent on the populations of CW microorganisms and plants. By developing microbial biofilms on the extensive surfaces of plant roots, wetlands facilitate the purification of water. The disinfection device is powered by solar energy during the final purification phase. Before being repurposed, this device disinfects purified effluent by utilizing UV light to eliminate hazardous pathogens. Rural regions lacking electricity infrastructure are particularly well-suited for solar water purification. The system employs renewable energy sources to mitigate its environmental impact and operating expenses. The solar system is comprised with solar batteries which store the powder during the day and use it later. UV disinfectants are a low-maintenance and effective last line of defence against maladies. Durability, affordability, and simplicity comprise the framework of the system. Sand, gravel, and native vegetation are inexpensive and straightforward to implement, which minimizes the costs of construction and maintenance. Anaerobic digestion, solar-powered disinfection, and artificial wetlands comprise a multi-barrier effluent treatment system. The system layout is illustrated in Figure 1. By employing a UV-based disinfectant and a multi-stage Anaerobic Baffled Reactor (ABR), it is evident that the effluent from the ABR ultimately reaches constructed wetlands (CW's).

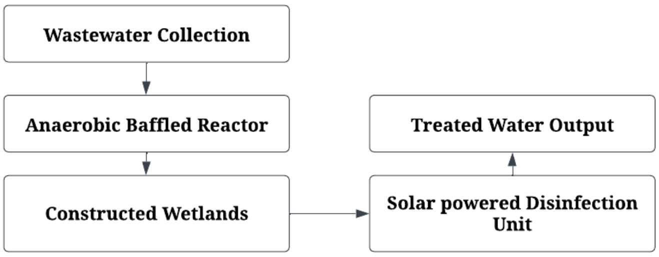

Figure 1: System Layout Diagram

2.2 Anaerobic Baffled Reactor (ABR) Implementation

The Anaerobic Baffled Reactor (ABR) is essential for the purification of effluent in rural areas that are decentralized. The ABR is the mechanism by which microorganisms in effluent break down organic molecules without oxygen in anaerobic digestion. The procedure reduces the concentration of organic pollutants and the biochemical oxygen demand (BOD), thereby rendering effluent suitable for disposal or treatment. The ABR is divided into sections by baffles, and wastewater is directed through them. Anaerobic microorganisms can decompose the organic content of effluent through prolonged reactor residency. Each component fosters an environment that optimizes anaerobic digestion by promoting bacterial interaction with organic contaminants. Upon entering the first chamber, anaerobic detritus is combined with influent effluent. The growth of anaerobic microorganisms is facilitated by the presence of an ideal pH and temperature. The effluent's flow channel through the reactor's compartments is extended by baffles. The architecture enables microbial populations to decompose organic substances into water, carbon dioxide, and methane. The sketch of ABR is illustrated in Figure 2.

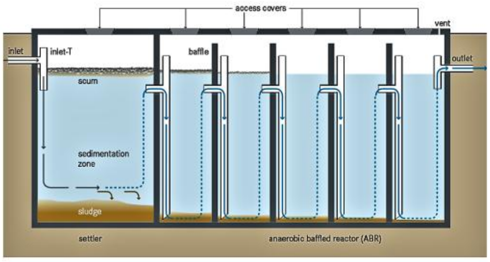

Figure 2: Anaerobic Baffled Reactor System

The ABR process enables the stabilization of organic molecules and the reduction of BOD, thereby reducing the production of sediment. Especially beneficial in remote regions with challenges with garbage disposal. Anaerobic digestion is advantageous for remote populations because it generates biogas that is utilized for sustainable energy. The efficacy of ABR is contingent upon the retention period, microbial concentration, and operating variables such as temperature and pH. The optimal performance of the system necessitates meticulous planning and execution. In order to ensure optimal assimilation and a healthy microbial population, it is necessary to modify the flow rate, temperature, and influent burden. The ABR can be employed to regulate rural wastewater in a sustainable and effective manner by decentralized wastewater treatment facilities. The ABR employs natural anaerobic digestion to reduce the organic burden of the effluent, the production of detritus, and the generation of energy. ABRs are essential for decentralized wastewater treatment systems due to these advantages; they enhance rural health and sanitation.

2.3 Constructed Wetlands (CW) Development

A significant advancement in ecologically conscious water management is the inclusion of Constructed Wetlands (CW) as an added purification component in decentralized wastewater systems. An economical and environmentally beneficial method of effluent remediation is the utilization of man-made wetlands that replicate their natural processes. The biological, chemical, and physical processes that these systems employ to purify effluent include water, vegetation, and bacteria. A constructed wetland treats effluent by directing it through a network of cells or basins, which employ substrates such as gravel, sand, or other wetland plants. The wetland's gravel and sediment strata at one end physically filter out particulate materials as the effluent flows through them. The sketch of CW treatment system is illustrated in Figure 3.

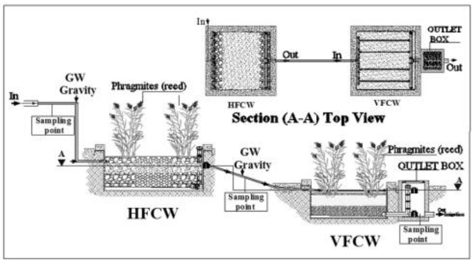

Figure 3: Sketch of Constructed Wetland Treatment System

The decomposition of organic contaminants by microbial populations in the rhizosphere is accelerated by the infiltration of water through the substrate and into the root zones of plants. The remediation procedure is significantly enhanced by the presence of vegetation in the newly created wetlands. They prevent the eutrophication of downstream bodies of water by absorbing nutrients, including nitrogen and phosphorus, from effluent. Biofilms are established on the roots of plants by microbes, which are essential for the degradation of organic matter. Biofilms contribute to the reduction of the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of the effluent by decomposing organic pollutants into simpler molecules. The levels of pollutants and infectious maladies are reduced as the water undergoes the biological degradation, filtration, adsorption, and sedimentation processes of the wetland. The provision of habitat for animals and the improvement of biodiversity are among the ecological advantages of artificial wetlands. The wetland's vegetation performs a variety of functions, such as calming the water through shadowing, augmenting the site's attractiveness, and providing opportunities for recreational activities. The long-term efficacy of manufactured wetlands is contingent upon proper management and maintenance. The purpose of these wetlands is to regulate plant growth, eliminate invasive species, and monitor water quality. The construction of artificial wetlands is a practical and long-term solution for the treatment of wastewater in rural regions playing a critical role in decentralized wastewater treatment systems as they can reduce contaminants, improve water quality, and improve environmental health.

2.4 Solar-powered Disinfection Unit Integration

Decentralized effluent disinfection systems that are powered by solar energy are both environmentally friendly and cost-effective. Consequently, purified water continues to be potable. The cleansed effluent is appropriate for agricultural irrigation or other non-drinking applications due to the destruction of bacteria and other organisms by UV radiation. UV radiation at 254 nm achieves disinfection of water. This wavelength disrupts the reproduction of bacteria and other microorganisms by damaging their DNA. There are numerous reasons why this disinfection machine is optimal for remote locations without reliable electricity, including solar power. The UV beams of disinfectant lamps are generated by solar panels. The effectiveness of UV disinfection is contingent upon the turbidity of the water, the duration of the exposure to UV light, and the intensity of the light. A consistent water passage rate through the UV chamber is maintained by the system to guarantee disinfection. By adjusting the flow rate, the optimal duration for the interaction between water and UV radiation is achieved, resulting in the desired outcome. The device assesses the condition of the solar panel and UV radiation in addition to cleansing water. This guarantees the continuous efficacy of disinfection. This maintenance plan necessitates the removal of biofilm and detritus from the lamps, which may obstruct UV light. Solar-powered disinfection apparatus is a safer and more environmentally friendly method of treating wastewater. The disinfection procedure is capable of enduring power disruptions and reaching remote areas as a result of its solar energy source. In rural areas, public health and environmental safety must be promoted by integrating microbiological safety measures with physical and biochemical effluent treatment.

2.5 Material Sourcing and Cost Management

In rural areas with limited resources, decentralized wastewater treatment systems encounter distinctive budget management and material procurement challenges. The durability and efficacy of these devices are contingent upon the availability of materials that are both affordable and readily accessible. This method prioritizes the use of cost-effective technologies that are compatible with the local ecology and locally sourced materials in order to address these issues. In order to reduce expenses and stimulate local economies, decentralized wastewater treatment systems implement local sediment, gravel, and vegetation. Sand and gravel are essential for the filtration and microbial development of substrates in man-made wetlands. Irrigation and other inputs may be reduced by native plants, which in turn reduces operating costs. Anaerobic baffled reactors (ABRs) should be constructed with local resources in mind. Solar-powered disinfection and construction are included. Local supplies and expertise in solar panel installation may be required to construct the solar-powered disinfection apparatus. The ABR's structural stability is guaranteed by its concrete structure. This enables the system to be serviced locally, resulting in cost savings. In order to guarantee the financial sustainability of a project, decentralized wastewater treatment systems implement early cost assessment, budgeting, and financial planning. The installation, maintenance, and periodic enhancements of treatment components are included in operating and capital costs. Financial planners incorporate grants, foreign aid, and community contributions when estimating future expenditures. By utilizing local resources and addressing rural economies, these systems may offer sustainable effluent treatment solutions.

2.6 Training

The efficacy of decentralized wastewater treatment facilities in rural communities is significantly influenced by education. The system necessitates extensive training for residents to operate, maintain, and repair it. Training enhances the local capacity to operate the system autonomously, thereby reducing the necessity for external assistance. The training should encompass the system's operation, safety regulations, routine maintenance, emergency response, protective apparel, equipment safety, response to chemical spills and power outages. The participants will acquire an understanding of the operation of the Anaerobic Baffled Reactor (ABR), constructed wetlands, and solar-powered disinfection unit in the effluent treatment system. By monitoring system state, modulating flow rates and retention periods, and comprehending component operation, students can enhance the efficacy of their treatments. In training programs, technical proficiency and community ownership are equally valued. The system may be administered, decided, and maintained by any resident of the neighbourhood. To ascertain the effectiveness of the training programs and identify areas for improvement, they implement feedback and evaluation. To measure the system performance, the biochemical oxygen demand reduction and removal efficiency are calculated by the following Eq(1) and Eq(2).

$$BOD\ Reduction\ (\%) = \frac{Initial\ BOD - Final\ BOD}{Initial\ BOD} \times 100 \tag{1}$$

$$Removal\ Efficiency\ (\%) = \frac{Concentration\ in\ influent - Concentration\ in\ effluent}{Concentration\ in\ influent} \times 100 \tag{2}$$

3. Results and Discussion

The BOD decline from Eq(1) can be employed to evaluate the efficacy of anaerobic reactors by comparing the beginning and ending BOD levels and determining the percentage decrease. By comparing the quantities of pollutants in the influent and effluent, the pollutant removal efficiency is a critical metric for assessing the efficacy of a treatment component. This metric determines the efficiency reduction from Eq(2). The adjacent tables offer a comprehensive analysis of the primary components of the decentralized wastewater treatment system. The Anaerobic Baffled Reactor (ABR) is illustrated in Table 1, which illustrates its dimensions, design, and efficacy metrics, including energy consumption and organic matter removal. Information regarding the Solar-powered Disinfection Unit, such as its capacity, pathogen reduction efficiency, UV light intensity, and contact time, is presented in Table 2. Table 3 displays the performance parameters that indicate the efficacy of the ABR in treating effluent. These measures include the percentage reduction in COD, input, and effluent biochemical oxygen demand (BOD), and total particulates (TSS). The practicality and efficacy of this decentralized wastewater treatment approach for rural regions are illustrated by these results, which underscore the interplay between the various components of the system that result in substantial reductions in pollutants. These technologies have the potential to establish sustainable water reuse systems that will be advantageous to future generations.

Table 1: Anaerobic Baffled Reactor (ABR) Implementation

Parameter	Value
Number of compartments	4
Dimensions (m)	2 x 1 x 1
Hydraulic retention time (d)	2
Organic matter removal efficiency	85 % BOD, 90 % TSS
Energy Consumption	Low

Table 2: Solar-powered Disinfection Unit Integration

Parameter	Value
UV light intensity (mW/cm^2)	30
Contact time (s)	20
Pathogen reduction	98.1
Solar panel capacity (kW)	1.5

Table 3: Performance Metrics for Anaerobic Baffled Reactor (ABR)

Metric	Value
Influent BOD (mg/L)	300
Effluent BOD (mg/L)	45
Influent TSS (mg/L)	250
Effluent TSS (mg/L)	25
Biogas production (L/day)	100
COD Reduction (%)	70

4. Conclusion

The installation of decentralized wastewater treatment facilities in more remote locations is a significant stride toward more environmentally favourable water management. Anaerobic baffled reactors, constructed wetlands, and solar-powered disinfection units are all components of these systems that collaborate to guarantee the safety of the effluent for reuse and to minimize the presence of contaminants. There are numerous benefits to utilizing locally sourced products and renewable energy sources, including the reduction of environmental impact and the promotion of local economies. For these systems to be long-term sustainable and to enable communities to operate and maintain them independently, it is essential to provide training and community engagement. Decentralized purification systems are a lasting and effective solution for wastewater management in rural areas, as they aid in the recovery of the environment and people following disasters.

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