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Smart and Sustainable Sewage Treatment System for Rural Areas Using Vetiver–Bamboo Hybrid Filtration with IoT Monitoring

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Abstract: *The project titled "Smart and Sustainable Sewage Treatment System for Rural Areas Using Vetiver–Bamboo Hybrid Filtration with IoT Monitoring" aims to provide a cost-effective, eco-friendly, and technologically advanced solution for wastewater management in rural regions such as Rajapur village. In most rural areas, untreated domestic sewage is discharged into open drains or nearby fields, leading to environmental pollution, groundwater contamination, and health hazards. Conventional sewage treatment plants (STPs) are expensive, energy-intensive, and difficult to maintain in small communities. To address these challenges, this project integrates natural phytoremediation techniques with modern IoT-based monitoring to develop a decentralized treatment approach suitable for local conditions.*

Keywords: Smart Sewage Treatment System, Sustainable Wastewater Management, Rural Sanitation, Vetiver Grass Filtration, Bamboo Filtration System, Hybrid Filtration Technique, Phytoremediation, Constructed Wetland, IoT Monitoring, Water Quality Sensors.

I. INTRODUCTION

Water is one of the most essential natural resources for human survival, agriculture, and industrial development. However, rapid urbanization, population growth, and inadequate sewage management systems have severely affected both the availability and quality of water resources worldwide. In India, especially in rural regions, untreated sewage is commonly discharged into open drains, agricultural lands, rivers, and nearby water bodies, causing significant environmental degradation and public health concerns [1]. Studies indicate that nearly 70% of India's surface water is polluted due to untreated domestic and industrial wastewater, with rural areas contributing substantially because of the absence of decentralized wastewater treatment facilities [2].

The improper disposal of sewage leads to contamination of groundwater and surface water sources, which are widely used for drinking, irrigation, and household purposes in villages. This contamination increases the spread of waterborne diseases such as cholera, dysentery, diarrhea, typhoid, and hepatitis, thereby affecting the health and quality of life of rural populations [3]. Furthermore, untreated wastewater negatively impacts soil fertility, aquatic ecosystems, and agricultural productivity, creating long-term socio-economic challenges for rural communities [4].

Conventional Sewage Treatment Plants (STPs) are generally designed for urban environments and require high capital investment, sophisticated infrastructure, continuous electricity supply, and skilled operators for maintenance. Although these systems are effective in treating wastewater in cities, they are often unsuitable for rural areas due to financial constraints, lack of technical expertise, and limited access to resources [5].

Rajapur village represents a typical example of these rural sanitation challenges. Similar to many villages in India, Rajapur lacks a functional sewage treatment facility, resulting in the direct discharge of household wastewater into nearby surroundings. This untreated sewage infiltrates into the soil and contaminates groundwater resources, which are the primary source of drinking water for residents. Farmers in the region have observed declining soil fertility and reduced agricultural productivity, while villagers frequently suffer from illnesses related to polluted water sources [6].

In recent years, nature-based wastewater treatment systems have emerged as effective and environmentally sustainable alternatives to conventional methods. Among these, phytoremediation techniques using plants such as Vetiver grass (*Chrysopogon zizanioides*) and bamboo have shown promising results in wastewater purification. Vetiver grass possesses a deep and dense root system capable of absorbing heavy metals, excess nutrients, suspended solids, and organic pollutants from sewage water [7]. Bamboo plants further enhance the treatment process by improving nutrient uptake, supporting beneficial microbial activity, and stabilizing the filtration bed structure. When combined with natural filtering materials such as gravel, sand, compost, and bamboo charcoal, these plants form a hybrid filtration system that mimics the purification processes of natural wetlands [8].

II. PROBLEM STATEMENT

In Rajapur village, domestic wastewater is discharged untreated into open drains and fields, causing groundwater pollution, foul odor, and health problems. This contamination affects aquatic life, degrades water quality, and poses risks to villagers who rely on the river for daily use. There is a need for a low-cost, eco-friendly, and easy-to-maintain solution that can effectively treat wastewater.

III. OBJECTIVES

- Develop a Hybrid Treatment System.
- Reduce Pollutant Levels.
- Integrate IoT-Based Monitoring.
- Ensure Minimal Maintenance.
- Promote Water Reuse

IV. LITERATURE SURVEY

1. Use of Vetiver Grass in Wastewater Treatment — Truong (2001)

Truong pioneered the use of Vetiver grass in wastewater treatment, demonstrating its ability to reduce BOD, COD, and heavy metal concentrations. The study proved Vetiver's potential for low-cost, decentralized rural treatment systems due to its deep root network and pollutant tolerance.

2. Bamboo-Based Wastewater Filtration System — Sinha and Virdi (2009)

Sinha and Virdi designed a bamboo-based wastewater filtration system utilizing gravel and sand beds. Their approach effectively removed suspended solids and organic pollutants, offering a sustainable and low-maintenance solution suitable for rural regions lacking advanced sewage infrastructure.

3. Horizontal Subsurface Constructed Wetlands — Sharma and Yadav (2015)

Sharma and Yadav developed horizontal subsurface constructed wetlands planted with Vetiver and local vegetation. Their system achieved more than 80% BOD removal with a detention time of 8–10 hours, proving its efficiency for small-scale rural sewage treatment.

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4. Domestic Wastewater Purification Using Vetiver — Ghosh et al. (2018)
Ghosh and colleagues evaluated Vetiver grass performance for domestic wastewater treatment. Results showed up to 80% BOD and COD removal, confirming that Vetiver roots enhance microbial degradation and pollutant adsorption processes.

5. Hybrid Constructed Wetlands — Singh and Gupta (2019)
Singh and Gupta introduced hybrid constructed wetlands combining vertical and horizontal flow systems with native vegetation. Their study demonstrated improved organic and nutrient removal efficiency, ensuring stable operation under fluctuating hydraulic and organic loads.

6. Natural Filter Media for Rural Treatment — Chaudhari et al. (2019)
Chaudhari and co-workers developed natural filtration units using sand, gravel, and activated charcoal. Their experiments revealed efficient removal of color, turbidity, and odor, recommending the system as an economical alternative for rural wastewater purification.

7. Phytoremediation Potential of Bamboo Species — Sharma and Dutta (2020)
Sharma and Dutta investigated the phytoremediation capacity of various bamboo species. The study found high removal efficiencies for nitrogen, phosphorus, and heavy metals, highlighting bamboo wetlands as eco-friendly and visually appealing treatment options.

8. Review of Constructed Wetlands in India — Khatri et al. (2020)
Khatri and associates reviewed constructed wetland systems across India. They reported that hybrid wetlands integrating Vetiver, Canna, and Bamboo achieved superior pollutant removal while maintaining energy efficiency and environmental sustainability.

9. Vetiver–Bamboo Hybrid Filtration System — Saini et al. (2020)
Saini and co-workers designed a Vetiver–Bamboo hybrid treatment unit achieving 85–90% reduction in suspended solids and nutrient load. Their findings emphasized the synergistic effects of both plant species in improving purification performance.

10. IoT-Based Real-Time Water Monitoring System — Patel et al. (2021)
Patel and colleagues developed an IoT-enabled monitoring system using pH, turbidity, and TDS sensors. The integration of IoT improved data accuracy and operational efficiency, making it suitable for decentralized wastewater treatment setups.

IV. WORKING OF SYSTEM

a) Wastewater Collection Section

The system begins with the collection of domestic wastewater generated from households, kitchens, bathrooms, and washing areas in rural communities. The sewage water is directed through underground or surface drainage pipelines into a primary collection chamber. In this chamber, large solid materials such as plastics, leaves, stones, and other floating waste are removed manually or using mesh screens. This initial filtration stage prevents blockage in the treatment system and ensures smooth flow of wastewater into the next processing unit. The collected wastewater is then transferred into the sedimentation tank for further treatment.

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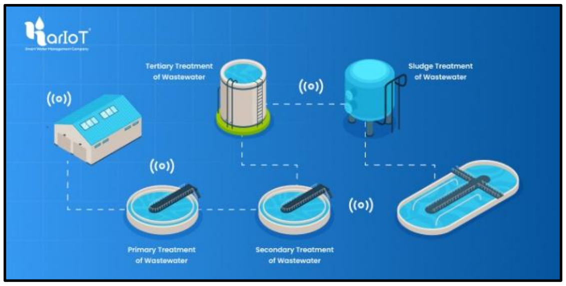

Fig 1: Block Diagram

b) Sedimentation and Primary Treatment Section

In the sedimentation tank, the wastewater is allowed to remain stagnant for a certain period so that heavier suspended particles settle at the bottom due to gravity. Oils, grease, and lightweight floating materials remain on the top surface and are removed separately. This process reduces the load of suspended solids entering the filtration bed and improves the efficiency of the biological treatment system. The partially clarified water from the sedimentation chamber is then passed into the hybrid filtration unit.

c) Vetiver–Bamboo Hybrid Filtration Section

The hybrid filtration section is the core treatment unit of the system. It consists of multiple natural filtering layers such as gravel, sand, bamboo charcoal, compost, and soil arranged sequentially. Vetiver grass and bamboo plants are grown on the filtration bed. As wastewater passes through these layers, physical, chemical, and biological treatment processes take place simultaneously.

The gravel and sand layers remove suspended impurities and reduce turbidity, while bamboo charcoal absorbs harmful chemicals and odors. The dense root system of Vetiver grass absorbs excess nutrients, heavy metals, and organic pollutants from the wastewater. Bamboo plants further support nutrient uptake and provide a suitable environment for beneficial microorganisms that help decompose organic matter.

d) IoT Monitoring and Sensor Section

To ensure efficient and continuous operation, the system is integrated with IoT-based monitoring technology. Various sensors such as pH sensors, turbidity sensors, temperature sensors, and TDS sensors are installed at different stages of the treatment process

The sensor data is collected using a microcontroller such as ESP32 or Arduino and transmitted to a cloud server or web dashboard through Wi-Fi or GSM communication modules. Villagers, operators, or local authorities can monitor the treatment

e) Treated Water Storage and Reuse Section

After passing through the hybrid filtration unit, the treated water is collected in a storage tank. The treated water becomes suitable for non-potable applications such as agricultural irrigation, gardening, toilet flushing, and cleaning activities. Reusing treated wastewater reduces dependence on freshwater resources and supports sustainable water management practices in rural areas.

f) Sludge Management and Environmental Sustainability Section

The solid waste and sludge collected during sedimentation are periodically removed and processed separately. Organic sludge can be converted into compost or biofertilizer for agricultural use, reducing waste generation and supporting

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sustainable farming practices. The use of natural materials such as Vetiver grass, bamboo, gravel, and sand makes the system environmentally friendly and economically affordable.

V. SYSTEM DESIGN

a) Input Wastewater Collection Unit Design

The input wastewater collection unit is designed to gather sewage water generated from households, kitchens, bathrooms, and washing areas within the rural community. A network of PVC drainage pipes is used to transport wastewater into a central collection chamber. The chamber is constructed using reinforced concrete or plastic storage tanks to ensure durability and leak prevention.

Fig 2: Domestic Wastewater Discharge Area In Rajapur Village

A mesh screen is installed at the inlet to remove large solid particles such as plastics, cloth pieces, leaves, and other debris. This section is designed to maintain a continuous flow of wastewater into the treatment system while preventing clogging and damage to downstream components.

b) Sedimentation Tank Design

The sedimentation tank is designed to perform primary treatment by separating heavier suspended particles from wastewater through gravity settling. The tank is rectangular or cylindrical in shape and is constructed using concrete, fiberglass, or plastic material. The tank includes inlet and outlet pipes placed strategically to ensure smooth flow and sufficient retention time for sedimentation.

Fig 3: Domestic Wastewater Discharge Area In Rajapur Village

The bottom portion of the tank is slightly sloped to facilitate sludge accumulation and easy removal. Floating materials such as oils and grease are trapped using baffles or skimming arrangements. This design reduces suspended solids before wastewater enters the hybrid filtration unit, thereby improving treatment efficiency and extending the life of the filtration media.

c) Vetiver–Bamboo Hybrid Filtration Bed Design

The hybrid filtration bed is the core component of the system and is designed using multiple natural filtration layers arranged vertically. The filtration bed consists of gravel, coarse sand, fine sand, bamboo charcoal, compost, and soil layers. Each layer performs a specific filtration function such as removal of suspended particles, odor absorption, nutrient retention, and microbial support.

Fig 4: Bamboo Filtration

Vetiver grass and bamboo plants are planted on the upper surface of the filtration bed. Vetiver roots penetrate deeply into the soil layers and absorb pollutants, while bamboo plants stabilize the structure and promote microbial activity. The filtration tank is designed with proper drainage outlets to allow uniform water flow through all layers. This section is developed based on constructed wetland principles to maximize wastewater purification efficiency using natural biological processes.

d) IoT Sensor and Monitoring System Design

The IoT monitoring section is designed to continuously observe the quality of wastewater during the treatment process. Sensors such as pH sensors, turbidity sensors, TDS sensors, water level sensors, and temperature sensors are installed at various stages of the system. These sensors are connected to a microcontroller unit such as ESP32 or Arduino.

VI. RESULTS

Introduction

The performance evaluation of the proposed Vetiver–Bamboo Hybrid Phytofiltration System integrated with IoT-based monitoring was carried out through physicochemical analysis of wastewater samples collected before and after treatment. The effectiveness of the system was determined by comparing the initial untreated wastewater characteristics with the final treated effluent quality after passing through all treatment stages

The treatment system demonstrated significant improvement in wastewater quality due to the combined action of:

- Sedimentation
- Physical filtration
- Rhizofiltration
- Phytoremediation
- Adsorption
- Microbial biodegradation

The analysis confirmed the technical feasibility of the proposed decentralized wastewater treatment system for rural applications.

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Comparative Water Quality Analysis

Parameter	Before Treatment	After Treatment	%Improvement / Reduction
pH	7.14	8.14	Stable
Turbidity (NTU)	113	13	88.5% reduction
Total Suspended Solids (mg/L)	380	180	52.63% reduction
BOD (mg/L)	242	42	82.64% reduction
COD (mg/L)	450	150	66.67% reduction
TDS (mg/L)	1654	1154	30.23% reduction
Chloride (mg/L)	363	303	16.53% reduction

Role of Vetiver in Pollutant Removal

Vetiver grass significantly improved treatment efficiency through:

1. Rhizofiltration

Removal of suspended solids.

2. Nutrient Uptake Absorption of:

Nitrogen Phosphorus

3. Root-Mediated Aeration Enhanced microbial degradation.

4. Pollutant Stabilization Immobilization of contaminants.

The deep fibrous roots increased hydraulic retention and biological activity.

Role of Bamboo in Pollutant Reduction

Bamboo plants contributed through:

- Secondary nutrient polishing
- Dissolved contaminant uptake
- Oxygen transfer enhancement
- Root-zone microbial support

The extensive root network improved overall filtration efficiency

Role of Activated Bamboo Charcoal

Activated bamboo charcoal improved final polishing through:

- Adsorption of dissolved organics
- Odor removal
- Color reduction
- Trace contaminant adsorption

Its high porosity and surface area enhanced tertiary treatment efficiency.

Time-Wise Water Quality Testing Report

Experimental Testing Data

Time	Turbidity (NTU)	TDS (mg/L)	pH
0 Hr	113	1654	7.14
30 Min	110	1620	7.18
1 Hr	95	1580	7.26
2 Hr	78	1505	7.38
3 Hr	62	1435	7.50
4 Hr	47	1370	7.63
5 Hr	34	1290	7.76

6 Hr	24	1225	7.89
7 Hr	18	1180	8.02
8 Hr	13	1154	8.15

VIII. FUTURE SCOPE

The proposed Smart and Sustainable Sewage Treatment System for Rural Areas Using Vetiver–Bamboo Hybrid Filtration with IoT Monitoring has significant potential for future development and large-scale implementation. As the demand for sustainable wastewater management increases, the system can be further improved through advanced technologies, automation, and expanded applications.

One of the major future scopes of the project is the integration of Artificial Intelligence (AI) and Machine Learning (ML) techniques for predictive analysis and smart decision-making

CONCLUSION

The proposed Smart and Sustainable Sewage Treatment System for Rural Areas Using Vetiver–Bamboo Hybrid Filtration with IoT Monitoring provides an effective, eco-friendly, and affordable solution for managing wastewater in rural communities. The study highlights the growing challenges of untreated sewage disposal, groundwater contamination, and waterborne diseases caused by the lack of proper sanitation infrastructure in villages such as Rajapur. Conventional sewage treatment plants are often expensive, energy-intensive, and difficult to maintain in rural areas, making sustainable alternatives essential.

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