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Autonomous Wastewater Treatment System for Rural Communities in the Province of Manabí, Ecuador

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ABSTRACT: This study aimed to develop and pilot an autonomous, decentralized wastewater treatment system to improve access to safe sanitation in rural communities lacking conventional infrastructure. An applied approach was adopted, focusing on system design, prototype development, pilot implementation, and IoT-based monitoring. The results indicate that the system is technically feasible, operationally reliable, and adaptable to local conditions, supported by automation and renewable energy integration. Overall, the proposed solution represents a sustainable and scalable alternative to centralized sanitation systems, contributing to public health protection, environmental conservation, and the achievement of Sustainable Development Goal 6.

KEYWORDS: Decentralized wastewater treatment; Autonomous sanitation systems; Sustainable water management.

I. INTRODUCTION

Access to safe drinking water and adequate sanitation remains a global challenge. According to United Nations data [1], approximately 2.2 billion people lacked access to safely managed drinking water services, 3.5 billion did not have adequate sanitation systems, and 2.0 billion had no access to basic hygiene services. This crisis has serious consequences for public health, the environment, and the socioeconomic development of affected communities.

One of the main factors exacerbating this problem is the lack of wastewater treatment systems in low-income rural and urban communities [2]. In the absence of such systems, wastewater contaminates natural water sources, facilitates the spread of diseases, and generates negative impacts on biodiversity. Furthermore, inadequate sanitation infrastructure hinders sustainable development and deepens social inequality [3].

Recent research highlights the increasing relevance of decentralized wastewater treatment systems as sustainable alternatives to centralized sanitation infrastructure, particularly in resource-limited and rural settings. Studies have documented diverse implementations of decentralized treatment technologies that improve effluent reuse, reduce environmental pollution, and enhance local water security [4], [5].

Such systems minimize transportation costs and environmental impact while enabling recycling for agricultural and non-potable uses [6]. Furthermore, critical reviews emphasize emerging trends and future perspectives in low-cost, locally adapted decentralized wastewater management approaches in developing regions [7].

Objectives and Justification

The objective of this project was to develop and implement an autonomous wastewater treatment system for rural communities that lack access to safe sanitation services. The proposal seeks to provide a sustainable and technologically viable solution to persistent gaps in water and sanitation infrastructure.

The justification of the project lies in the multiple levels of value it generates by addressing the water and sanitation crisis through an integrated and sustainable approach. At the community level, the system would enable access to clean and safe water, contributing to the reduction of waterborne diseases and to an overall improvement in quality of life [8]. In addition, community empowerment and participation are promoted through training for system operation and maintenance, which may also create local employment opportunities. A key benefit is environmental conservation, as the system would reduce the discharge of contaminated wastewater into soils and rivers [9].

From the public sector perspective, the project supports compliance with sanitation policies aligned with Sustainable Development Goal 6, which aims to ensure the availability and sustainable management of water and sanitation for all [1], [10]. It also contributes to reducing public health expenditures by lowering the incidence of diseases associated with cross-contamination, thereby decreasing the burden on hospitals and health centers.

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In terms of infrastructure, the system represents a sustainable alternative to costly sewer networks that are often financially unfeasible for local governments.

For private companies and entrepreneurs, the project offers investment opportunities through the development of innovative wastewater treatment technologies and the creation of public–private partnerships [11]. These alliances may facilitate the implementation of sustainable solutions in other underserved rural and urban areas lacking access to safe water resources. Moreover, within a circular economy framework [12], the project encourages the reuse of treated water for irrigation or small-scale manufacturing processes, contributing to a reduction in excessive water consumption.

Scope of the Project

The expected deliverables include the design and implementation of an autonomous wastewater treatment system prototype, its installation in pilot communities, and community training for system operation and maintenance. The project also includes the deployment of an IoT-based monitoring system with remote access, as well as the preparation of environmental and social impact reports.

The main activities encompass research and development focused on the design of the mechatronic system; fabrication and testing through prototype construction and laboratory validation; pilot implementation in a selected community; community training workshops on operation and maintenance; and monitoring and evaluation through data collection and system optimization.

The resources required include technological components such as IoT sensors, nanofilters, bioreactors, and solar energy systems; human resources including engineers, technicians, and community training personnel; and financial resources obtained from government funds, private investment, and non-governmental organizations.

II. METHODS

This study adopted an applied, design-oriented approach aimed at developing and piloting an autonomous wastewater treatment system for rural communities without access to safe sanitation. The methods were structured in sequential phases aligned with the project life cycle.

An initial diagnostic and feasibility phase was conducted to identify sanitation needs and assess technical and economic viability under local environmental conditions. Based on these findings, the system was designed using a mechatronic framework that integrates physical, biological, and chemical treatment processes supported by renewable energy and IoT-based monitoring.

A prototype was then fabricated and validated through laboratory testing, evaluating key parameters such as flow rate, turbidity, pH, and contaminant removal efficiency. The validated system was subsequently deployed in a pilot community, accompanied by training activities for local operation and maintenance.

System performance was monitored using real-time data collected through embedded sensors and a remote IoT platform. This monitoring phase enabled continuous evaluation of operational reliability, water quality, and environmental and social impacts, supporting system optimization.

III. RESULTS

Description of the Solution

The proposed solution is structured around the project life cycle, ensuring an orderly, feasible, and sustainable implementation process.

During the initiation phase, the problem is identified and the project is formally formulated, followed by the search for strategic partners and funding sources. At this stage, a technical and economic feasibility analysis is conducted to determine the viability of the autonomous wastewater treatment system within the target context.

The planning phase focuses on the detailed design of the Autonomous Wastewater Treatment System. This includes the selection of appropriate materials and suppliers, the definition of the pilot community, and the development of a comprehensive risk management and logistics plan to guide implementation.

In the execution phase, the system is fabricated and installed in the selected community. This phase also includes community training activities aimed at building local capacity for system operation and maintenance, as well as functionality testing and necessary technical adjustments.

The monitoring and control phase involves continuous tracking of system performance, data collection related to water quality and usage, and the application of preventive and corrective maintenance measures to ensure long-term efficiency and reliability.

Finally, the closure phase focuses on evaluating the overall impact of the project, assessing its potential scalability to other communities, and presenting the results to investors and government stakeholders to support replication and expansion.

Risk Management Approach

The project incorporates a structured risk management strategy aimed at identifying, assessing,

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and mitigating potential threats that could affect implementation and long-term sustainability. The main risks, their estimated impact, and the corresponding mitigation strategies are summarized below.

Table 1: Risk Identification and Mitigation Strategies

Risk	Impact	Mitigation Strategy
Lack of funding	High	Establish partnerships with NGOs and public and private sector actors; apply for sustainability and development funds.
Technology failure	Medium	Conduct rigorous testing prior to implementation; adopt a modular system design to facilitate maintenance and upgrades.
Community rejection	Medium	Implement awareness-raising programs and participatory training to promote acceptance and ownership.
Adverse environmental conditions	Medium	Adapt the system design to extreme climatic conditions; use durable and resistant materials.
Lack of community-based maintenance	High	Provide technical training and create local incentives to ensure continuous maintenance.

Equipment Operation Diagram

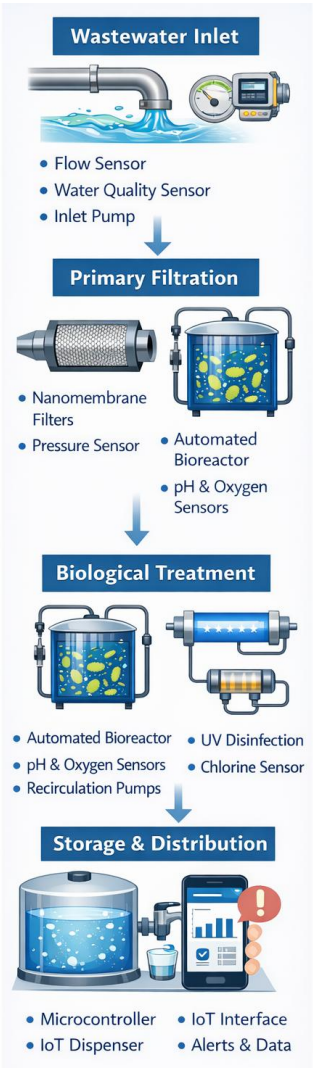

Figure 1. Wastewater Treatment Process

The diagram (Figure 1) begins with the wastewater inlet, followed by primary physical filtration, biological treatment through an automated bioreactor, and secondary filtration based on chemical and ultraviolet processes. Subsequently, the treated water enters the storage and distribution stage, while the entire system is continuously supervised through an IoT-based remote monitoring and control module. This visual representation clearly and systematically synthesizes the operational stages of the proposed system, highlighting its integrated and automated approach.

A. Wastewater Inlet:

- A flow sensor detects the volume of incoming water.
- A water quality sensor measures initial contaminant levels.
- An inlet pump regulates the flow into the system.

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B. Primary (Physical) Filtration:

- Nanomembrane filters remove solids and large particles.
- A pressure sensor monitors potential filter blockages.

C. Biological Treatment (Automated Bioreactor):

- Bacteria break down organic contaminants.
- pH and dissolved oxygen sensors regulate the bioreactor environment.
- Automated valves and pumps control water recirculation.

D. Secondary Filtration (Chemical and Ultraviolet):

- Turbidity and conductivity sensors verify the level of treatment.
- A UV disinfection module eliminates bacteria and viruses.
- A chlorine sensor measures dosage when required.

E. Storage and Distribution:

- Treated water is stored in a secure tank.
- An automated dispenser with IoT control manages distribution.
- Level sensors monitor the available water volume.

F. Remote Monitoring and Control (IoT)

- A microcontroller processes data and adjusts parameters in real time.
- An IoT interface allows system status visualization through a mobile application.
- Alarms notify system failures or the need for preventive maintenance.

Discussion of the Proposed System

The proposed autonomous wastewater treatment system demonstrates that structuring implementation around the project life cycle improves technical feasibility, operational coherence, and sustainability. The integration of physical, biological, and chemical–ultraviolet treatment processes within a decentralized and automated framework enhances treatment efficiency and adaptability to local conditions [13]. Real-time monitoring through sensors and IoT-based control enables continuous performance optimization, positioning the system as a flexible alternative to conventional centralized sanitation infrastructure in resource-limited contexts [14].

From a sustainability perspective, the results highlight the importance of risk management and community involvement in ensuring long-term functionality. Financial, technological, and social risks are mitigated through modular design, preventive maintenance, and participatory training strategies. The incorporation of remote monitoring and automated control supports system scalability and replication, reinforcing the potential of the proposed solution to contribute effectively to decentralized sanitation initiatives aligned with Sustainable Development Goal 6 [1], [10].

IV. CONCLUSION

The lack of wastewater treatment systems is a structural factor that exacerbates health, environmental, and social inequalities in rural and low-income communities. Insufficient sanitation increases waterborne diseases, degrades ecosystems, and constrains socioeconomic development, directly conflicting with the objectives of Sustainable Development Goal 6.

Decentralized and automated wastewater treatment systems constitute a technically and socially viable alternative to conventional sewerage infrastructure. The proposed Autonomous Wastewater Treatment System overcomes economic and geographic constraints through the integration of mechatronic technologies, renewable energy, and IoT-based monitoring.

The integration of advanced treatment technologies enhances system efficiency, sustainability, and operational resilience. Nanomembrane filtration, automated bioreactors, real-time sensors, and remote monitoring enable continuous control, optimized resource use, and reduced dependence on external technical intervention.

Community participation and technical training are essential for long-term system sustainability. Local capacity building, operation and maintenance training, and incentive mechanisms mitigate risks related to cultural resistance and system abandonment.

The proposed system directly contributes to SDG 6 while generating multisectoral benefits. It improves access to sanitation, reduces public health costs, enables public–private partnerships, and supports circular economy practices through the reuse of treated water, demonstrating strong potential for scalability and replication.

SOME OF THE ADVANAGES FROM THE ABOVE RESULTS

a) Improves access to safe water and sanitation in underserved rural communities.
b) Reduces waterborne diseases and associated public health costs.
c) Enables decentralized and cost-effective sanitation solutions where conventional infrastructure is not feasible.
d) Enhances system sustainability through the integration of renewable energy and

automation.

e) Supports scalability and replication in other rural and low-income contexts.

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