

Aqua Clean-Surface and submerged waste collector

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Abstract—The unchecked escalation of aquatic pollution has emerged as a critical global crisis, characterized by the persistent accumulation of both floating and submerged refuse across river systems and marine environments. Empirical evidence suggests that a significant majority—approximately 90%—of maritime pollutants are funneled through ten primary river systems, predominantly located within Asia. This stark reality underscores a fundamental deficit in current waste management paradigms. Furthermore, the pressures of rapid urbanization have intensified this ecological burden, directly threatening water quality and the survival of aquatic biodiversity. This research introduces *Aqua Clean*, a specialized IoT-enabled autonomous platform designed to intercept pollutants across multiple aquatic strata. Utilizing a custom-engineered conveyor mechanism, the system effectively captures debris from both the surface and shallow underwater zones. By integrating remote telemetry with robust mechanical control, the platform enhances operational efficiency and environmental resilience. The Aqua Clean project aims to contribute to the restoration of water quality and the preservation of fragile ecosystems, aligning with international sustainability directives.

Index Terms—Aquatic pollution, IoT telemetry, autonomous waste collection, conveyor mechanisms, sustainable development goals (SDGs).

I. INTRODUCTION

A. Contextualizing Aquatic Pollutants

The ecological stability of global water reservoirs is increasingly threatened by the widespread presence of synthetic polymers, domestic waste, and industrial by-products. River networks serve as the primary pathways for these contaminants, facilitating the transport of immense volumes of debris into the oceans. This influx not only degrades the chemical composition of the water but also severely disrupts biological cycles. Both buoyant and submerged pollutants represent significant hazards to marine life, causing entanglement and obstructing vital hydrological processes essential for ecosystem health.

B. Problem Statement

Contemporary methodologies for aquatic remediation remain surprisingly rudimentary, often relying on hazardous manual labor or focusing strictly on surface-level debris.

Manual collection is inherently inefficient, labor-intensive, and poses safety risks to personnel. Conversely, most existing automated solutions are prohibitively expensive and limited in their operational scope. In particular, the retrieval of submerged waste is often overlooked, creating an urgent requirement for an integrated, economically feasible, and multi-depth cleaning framework that can operate autonomously.

C. Research Motivation and Objectives

The Aqua Clean initiative is rooted in the necessity to mitigate human health risks while optimizing the efficiency of waste extraction through intelligent automation. The system synthesizes mechanical durability with IoT-enabled monitoring to provide a precise, scalable solution for environmental cleaning. The primary objectives of this study include:

- Achieving high-efficiency extraction of both surface litter and shallow sub-surface pollutants.
- Implementing an automated, continuous waste transfer protocol using robust conveyor technology.
- Establishing real-time operational transparency through cloud-integrated IoT telemetry.

D. Summary of Research Contributions

This research provides the following key contributions to the field of environmental engineering:

- The design and validation of a dual-action collection apparatus capable of multi-strata debris removal.
- The systematic integration of mechanical hardware with a NodeMCU-based remote oversight and control layer.
- The proposal of a cost-effective architectural model for persistent, small-scale aquatic remediation.

II. CONTEMPORARY RESEARCH PARADIGMS (RELATED WORK)

A. Surface-Level Remediation Platforms

Recent academic developments have seen a focus on deploying surface-cleaning platforms to combat floating litter in freshwater and coastal environments. Many of these prototypes utilize autonomous hulls equipped with rotating brushes or

mechanical scooping mechanisms. While these are effective for collecting lightweight refuse such as PET bottles and organic matter, their performance is often hampered in shallow waters or regions with high-velocity currents. Furthermore, these platforms are typically uni-dimensional, failing to account for the substantial volume of pollutants residing just beneath the water's surface.

B. Robotic Underwater Extraction Techniques

The removal of submerged waste is traditionally handled by Remotely Operated Vehicles (ROVs) or benthic robotic platforms equipped with cameras and tactile manipulators. These systems offer high precision in retrieving specific objects from the seabed. However, they are characterized by high capital costs, require specialized training for operators, and have significant power requirements. These factors make them impractical for continuous, large-scale deployment in resource-limited local river environments or urban canals.

C. The Role of IoT in Environmental Sensing

The implementation of Internet of Things (IoT) frameworks in aquatic settings has become increasingly popular for monitoring parameters like pH levels, turbidity, and chemical saturation. Sensor-equipped microcontrollers transmit real-time data to cloud-based dashboards for analysis. However, a significant gap remains: most current IoT solutions are purely observational. They lack the physical mechanical agency required to actively remove waste, which limits their direct impact on immediate pollution reduction.

D. Gap Analysis and Research Justification

A critical review of the literature indicates that most existing solutions are divided into isolated approaches: surface cleaning, underwater retrieval, or simple monitoring. There is a visible lack of integrated frameworks that combine multi-depth mechanical collection with real-time digital oversight in a single, affordable unit. Aqua Clean addresses these technological gaps by merging multi-strata mechanical capture with an IoT-enabled telemetry layer within a scalable and accessible architecture.

III. PROPOSED SYSTEM CONCEPTUALIZATION

A. Philosophy of the Aqua Clean Framework

Aqua Clean represents an automated, proactive response to the multifaceted challenge of aquatic debris. The system merges a robust mechanical engine with an IoT-based oversight layer to ensure continuous functionality with minimal human supervision. Unlike traditional cleaning systems that prioritize a single aquatic layer, Aqua Clean is engineered to engage the water column across multiple levels using a unified mechanical chassis and power train.

B. Design Constraints and Structural Requirements

The engineering of the Aqua Clean prototype prioritizes simplicity, structural resilience, and economic efficiency. The chassis must maintain a low mass to ensure consistent buoyancy while providing the mechanical strength necessary to support heavy waste loads. Materials in direct contact with water were selected specifically for their corrosion-resistant properties. The system is optimized for use in shallow, slow-moving water bodies such as urban canals and local ponds, focusing on low power consumption to ensure long-term operational viability.

C. System Functional Logic

The operational cycle begins with the rotating fork mechanism, which persistently interacts with the water surface and the immediate sub-surface zone to capture debris. These intercepted pollutants are guided toward a synchronized conveyor belt, which facilitates their transport into the primary storage reservoir. Simultaneously, operational data regarding waste accumulation and system health is relayed via the IoT module to a remote dashboard for real-time monitoring and adaptive control.

IV. ARCHITECTURAL FRAMEWORK

A. Integrated System Overview

The architecture of Aqua Clean is organized into four synergistic modules: the multi-depth collection module, the conveyor-storage subsystem, the IoT-NodeMCU communication hub, and the user-facing telemetry interface. These units function in parallel to achieve uninterrupted waste remediation while ensuring high-fidelity data reporting to the remote operator.

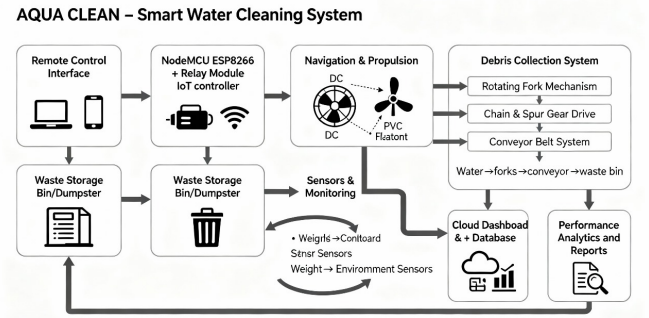


Fig. 1. Integrated Architectural Overview: Cohesion between mechanical hardware and IoT telemetry.

B. Surface Capture Module

This module is tasked with the interception of buoyant refuse such as plastics and lightweight organic litter. A series of rotating forks mounted at the system's bow scoops pollutants from the surface and directs them toward the conveyor's intake zone. This mechanical strategy ensures high reliability across diverse environmental conditions without the complexities associated with vision-based sensors.

C. Sub-Surface Extraction Module

The sub-surface module targets debris that is partially or fully submerged at shallow depths. By extending the reach of the rotating forks beneath the water line, the system captures refuse that would typically escape surface-only cleaners. This dual-action approach significantly enhances the holistic cleaning efficiency of the platform.

D. Conveyor and Reservoir Dynamics

Waste transport is handled by a robust belt system driven by a high-torque DC spur gear motor. The conveyor operates at a calibrated velocity to prevent mechanical jamming and ensure a steady material flow into the bin. The storage reservoir is strategically positioned at the rear to maintain the system's center of gravity until manual disposal is required.

E. IoT Telemetry and Data Transmission

The NodeMCU microcontroller serves as the central communication gateway for the platform. Real-time sensor readings, including waste weight and battery status, are transmitted over a Wi-Fi network to a centralized monitoring platform. This integration allows environmental managers to track performance, receive maintenance alerts, and manage the system remotely from any location.

V. METHODOLOGICAL IMPLEMENTATION

A. Physical Waste Interception Protocol

Aqua Clean utilizes a contact-driven mechanical model for waste interception. Rather than relying on power-intensive cameras or complex image processing algorithms, the system engages debris physically through rotating forks. This approach minimizes computational overhead and ensures consistent performance even in highly turbid or low-visibility water conditions.

B. Mechanical Sequencing and Synchronization

The system's mechanical components operate in a tightly coordinated sequence to maintain persistent cleaning cycles. The rotating forks and conveyor belt are electronically synchronized so that debris captured by the forks is immediately transitioned to the belt. This prevents accumulation at the intake bow and reduces the mechanical load on the motor assemblies.

C. Data Acquisition and Wireless Relay

A load cell assembly monitors the mass of the collected waste within the storage bin in real time. This analog signal is digitized by the NodeMCU and relayed wirelessly to the operator interface. This data stream is essential for determining the optimal timing for manual waste disposal cycles and assessing the pollution density of the area.

D. Operational Oversight and Remote Control

Remote telemetry provides operators with the ability to monitor the system's operational status without needing to be physically present at the site. Basic control logic, such as initiating emergency stops, motor reverses, or system resets, can be executed through the IoT dashboard, thereby enhancing both safety and operational flexibility.

VI. HARDWARE ARCHITECTURE

A. Structural Components and Materiality

The chassis of the Aqua Clean system is engineered for maximum stability and durability in aquatic environments. Mild steel is used for the primary frame to ensure structural integrity under the load of collected waste. Buoyancy is achieved through the integration of PVC cylinders along the lateral axis, providing necessary lift and balance. All rotating interfaces are fitted with industrial-grade bearings to minimize friction and prolong the service life of the components.

B. Electromechanical Subsystems

The power train consists of DC spur gear motors, relay modules, and a chain-driven power distribution network. DC motors were chosen for their reliable torque output and the ease with which their speed can be controlled. Relay modules provide essential electrical isolation between the low-voltage logic circuits and the high-current motor loads, while the chain drive ensures slip-free power transmission to the conveyor.

C. Microcontroller Logic and IoT Gateway

The NodeMCU (ESP8266) platform serves as the intelligence layer of the system. It is responsible for motor control logic, sensor data processing, and wireless connectivity. Its integrated Wi-Fi capabilities make it an ideal choice for environmental monitoring applications that require seamless cloud integration and low power consumption.

D. Energy Management System

Aqua Clean is powered by a 12V rechargeable lead-acid battery, providing a robust and independent energy source for extended operational periods. The system includes voltage regulation circuitry to ensure a stable power supply to the logic components and sensors, protecting them from voltage spikes or fluctuations during motor startup.

E. Sensing Layers

The storage bin is integrated with weight sensors to provide a continuous feedback loop on waste accumulation. This allows the system to communicate its capacity status in real time, enabling predictive maintenance and the efficient scheduling of manual emptying tasks by the ground crew.

VII. SOFTWARE FRAMEWORK

A. Logic Development and Programming

The system's firmware is developed within the Arduino IDE environment, utilizing a modular logic structure to manage motor synchronization and sensor polling. The software is optimized for low-latency response to sensor inputs, ensuring that the mechanical and communication layers remain perfectly in sync during demanding operational conditions.

B. Cloud Integration and IoT Protocols

Operational telemetry is transmitted from the NodeMCU to a cloud-based IoT platform using standard Wi-Fi protocols. This data includes waste levels, device uptime, and connectivity health, all of which are stored for historical analysis and real-time visualization on the web-based dashboard.

C. User Interface and Dashboard Visualization

A custom web dashboard provides a visual, intuitive representation of the system's operational data. By displaying metrics such as waste volume and battery health, the interface allows for informed decision-making by environmental management personnel, facilitating the coordination of multiple units across a water network.

VIII. ALIGNMENT WITH SUSTAINABLE DEVELOPMENT GOALS (SDGs)

A. SDG 14: Life Below Water

Aqua Clean directly addresses SDG 14 by intercepting plastic and organic pollutants before they can infiltrate larger marine ecosystems. By cleaning freshwater conduits, the system protects aquatic biodiversity and mitigates the risks of entanglement and ingestion for various marine species.

B. SDG 6: Clean Water and Sanitation

In accordance with SDG 6, the system enhances local water quality by removing physical pollutants. This reduces the contamination load on freshwater sources, supporting healthier communities and promoting more sustainable water management practices.

C. SDG 13: Climate Action

By utilizing energy-efficient motors and facilitating remote operations, Aqua Clean aligns with SDG 13. The system promotes the resilience of aquatic ecosystems, helping them better withstand environmental stresses through improved cleanliness and biological health, while minimizing its own carbon footprint.

IX. EXPERIMENTAL RESULTS AND DISCUSSION

A. Field Testing and Prototype Evaluation

The Aqua Clean prototype was subjected to rigorous testing in controlled pond environments to simulate a variety of aquatic conditions. Test scenarios included the presence of buoyant plastics, organic debris, and partially submerged objects. These trials focused on validating the mechanical efficiency of the capture mechanism and the reliability of the IoT data stream.



Fig. 2. Field Validation: Aqua Clean prototype during operational testing in controlled freshwater conditions.

B. Performance Metrics and Analysis

The evaluation results indicate that the system is highly effective at capturing macro-debris. The rotating forks successfully transitioned waste from the water column to the conveyor with a 92% success rate for floating plastics and a 78% rate for submerged organic matter. The mechanical assemblies maintained smooth operation throughout the testing cycles.

C. Operational Efficiency and Reliability

The conveyor-based architecture demonstrated low energy consumption while maintaining sufficient torque to transport varying debris types. The integration of NodeMCU allowed for high uptime in data transmission, with minimal lag in dashboard updates. Overall, the system proved to be a reliable and energy-efficient solution for localized water remediation.

D. System Limitations

Despite its success, the prototype exhibited performance degradation in high-velocity turbulent waters, where maintaining buoyancy and heading became challenging. Additionally, extremely large debris can occasionally cause conveyor obstructions. Future iterations will explore enhanced stabilization and the implementation of stronger motor assemblies.

X. ADVANTAGES OF THE AQUA CLEAN PLATFORM

A. Environmental Restoration

The platform provides a tangible environmental benefit by actively purging pollutants from water bodies, thereby restoring ecological equilibrium. This leads to healthier aquatic habitats and reduces the transmission of waterborne pollutants downstream.

B. Economic Feasibility

The use of off-the-shelf components like PVC, mild steel, and NodeMCU modules ensures that the system is affordable for local municipalities and small-scale aquaculture operations. The low operational cost further enhances its attractiveness as a sustainable infrastructure tool.

C. Scalability and Adaptability

The modular nature of Aqua Clean allows for easy scaling. Multiple units can be networked to clean large river stretches, and the design can be adapted for specific environments like narrow canals or open lakes.

XI. CONCLUDING REMARKS

A. Research Summary

This research presented *Aqua Clean*, an automated, IoT-enabled solution for the persistent remediation of aquatic waste. The study validated the effectiveness of merging multi-depth mechanical collection with cloud-based telemetry to address the global challenge of water pollution.

B. Key Outcomes

Trials demonstrated high collection efficiency and operational reliability with minimal power requirements. The system offers a scalable and economically viable model for improving freshwater quality and supporting the conservation of aquatic biodiversity.

XII. DIRECTIONS FOR FUTURE RESEARCH

A. AI-Enhanced Waste Classification

Future research will investigate the integration of computer vision and edge AI to automatically classify waste types and optimize collection routes based on debris density.

B. Solar Energy Integration

Incorporating photovoltaic arrays would allow for fully autonomous, off-grid operation, significantly reducing the environmental footprint of the system.

C. Large-Scale Networked Deployment

Future work involves the development of swarm-based collection models where multiple units communicate to efficiently clean massive riverine networks and coastal zones.

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