Design and Development of a Solar-Powered Autonomous Floating Bot for Water Quality Monitoring and Surface Cleaning

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Abstract
Over time, freshwater systems have encountered issues such as pollution, floating debris, and decreasing water quality, resulting in an increasing need for a low-cost, scalable, and energy-efficient monitoring solution. Traditional water sampling techniques require extensive labor, have limited sampling coverage, and lack a real-time component. In this study, we provide the design and development of a solar-powered, IoT-enabled floating bot that can function independently, monitor critical water-quality values, and help remove waste from the surface level. The bot is powered by a 20 W photovoltaic module, a 12.6 V, 1800 mAh Li-ion battery, and electrical components that allow for renewable-energy-based operation of the device. A microcontroller (ESP32) works as the processing and connectivity hub and connects to sensors (DHT11 for ambient parameters, DS18B20 for water temperature, analog turbidity sensor, and the pH probe). Two continuous rotation servo motors actuate the propeller method of navigation; and onboard Wi-Fi provides remote access and a dashboard for real-time monitoring of sensor readings. Experimental evaluations demonstrate that the solar panel can generate up to 72 Wh/day of usable energy, enabling continuous monitoring and up to 2.6 hours of cruising on battery alone. With a 14 Wh/day positive energy balance under typical 4.5 peak sun hours, the system is effectively energy self-sustaining. Sensor observations for pH, turbidity, and temperature remained stable and accurate within expected tolerances, validating the platform's capability for environmental assessment. Overall, the developed prototype offers a low-cost, sustainable, and scalable solution for water-quality monitoring and floating waste collection, with future potential for autonomous navigation, obstacle avoidance, and AI-driven water treatment recommendations.

Keywords: *Solar-powered water monitoring, IoT-enabled floating bot, water-quality assessment, turbidity sensing, pH sensing, renewable-energy-based system, ESP32 microcontroller, autonomous environmental monitoring, floating waste collection, real-time data acquisition, low-cost scalable prototype.*

Introduction

Freshwater environments are being increasingly threatened by pollution, loose plastic, and nutrient overloads, disrupting ecosystem services and presenting public health risks. Current monitoring programs rely on regular manual sampling and laboratory analysis, which tend to be labor-intensive, expensive, and have limited temporal resolution—they do not allow for the rapid detection of contamination events. Commercial alternatives (i.e., fixed sensor buoys, manned survey vessels, and high-end unmanned surface vehicles) can offer a higher level of automation, but the cost is often prohibitive, they consume energy, and/or are difficult to deploy at scale in developing and remote regions. This article describes a low-cost floating robot powered by solar energy and developed for continuous water-quality monitoring and surface debris removal. The prototype incorporates an ESP32 microcontroller and sensor suite composed of a DHT11 for ambient conditions, a DS18B20 for water temperature, an analog turbidity sensor, and a probe for pH; differential propulsion is based on dual continuous-rotation servos with a third for debris removal. The energy design is centered around a 20-W solar photovoltaic panel and a 12.6-V, 1.8-Ah (1800-mAh) battery; the panel provides about 90 Wh/day gross (~4.5 peak sun hours) to about 72 Wh/day (80% system efficiency). The battery can provide 22.68 Wh nominal (~18.14 Wh usable at 80% DoD). Calculated measurements show the average electronics draw at ~2.0 W idle and ~7.0 W when cruising and debris operations are happening; and the system meets about ~2.6 h of battery-only cruising and a minimum of ~14 Wh/day surplus energy given a cruising profile of 2 h per day.

Literature Review

1. Zohedi et al. (2025) – USV for Water-Quality Monitoring: The researchers tackled the growing concern of decentralized monitoring of freshwater due to pollution, and inability to monitor freshwater trends with limited human sampling techniques. They created a hemisphere-shaped unmanned surface vehicle (USV) that incorporated temperature, pH, and turbidity sensors in a real-time data stream via Bluetooth technology (IoT). The USV was equipped with brushed DC motors, demonstrated steady maneuverability, and remained 89% positively buoyant. The testing was successful in demonstrating reliable sensor readings, and the user engagement was positive considering control was achieved using a gamepad mobile interface and intuitive control. However, the limitations exist in longevity of endurance, calibration in dynamic waters, and autonomy for a multi-sampling mission. The gap in our research is pursuing intelligent navigation efforts, a multi-parameter sensor expansion, and incorporating debris-collection capabilities within the same system.

2. Akbari and Kolsuz (2025) - IoT Solar Buoy with Multi-Sensor Suite
This thesis addressed the need for continuous monitoring of water quality in renewable energy systems for remote aquatic applications. The authors constructed a solar buoy with an ESP32 based and LoRaWAN communication to measure DO, EC, turbidity, salinity, temperature, pH, and chlorophyll. The systems were tested in the field near Malmö and showed stable energy neutral characteristics even during periods when solar illumination was low. The communication distances were over 200 m with reliable packet delivery. However, when two sensors were activated simultaneously, interference resulted in negative pH values and inflated EC/DO responses. Sequential activation provided better reliability but limited mobility and coverage of larger areas. The research gap lies in combining mobile platforms (boats/USVs), long range mesh networks, and adaptive sampling patterns.

3. Gowda (2025) – Solar-Powered Surface Cleaning Robot for Lakes
This research examined the extensive accumulation of floating debris in lakes, partly a result of plastic pollution and partly due to inefficient methods of physical removal. The authors designed an autonomous cleaning robot powered by solar energy that could include a conveyor system to collect floating debris. The prototype was able to clean lightweight debris in an open water surface area under controlled testing but did not provide any quantitative assessment of cleaning efficacy, rate of cleaning under heavy debris, and duration of operational capacity. The system did not incorporate water-quality sensors, reducing the potential for broader environmental monitoring. The gap between the discovery and the limitation was examining the deployment performance in real-world environments as well as using multi-modal sensing methods and stable operation in wind-driven waves.

4. Temilolorun & Singh (2024–25) – Low-Cost USV for Aquaculture
The purpose of this paper was to explore solutions to navigation and sampling issues in aquaculture ponds with limited space for maneuverability by manned boats. A 3D-printed catamaran USV utilizing ROS, GNSS, IMU, and EKF-based sensor fusion was designed for this purpose. Turning-circle basin testing proved excellent maneuverability in the small-radius capabilities for operation in shallow ponds. The USV provided high-precision localization but did not integrate multi-parameter water-quality sensors or the ability to perform automated missions. The need for the research stems from the apparent gaps in integrating comprehensive water-quality suites, long-term reliability testing, and automated path-planning for optimized aquaculture productivity.

5. Chaarmart et al. (2024) – Solar Wireless Water-Quality Monitoring Boat
The study looked at pollution in Nonghan Lake in Thailand as a result of domestic wastewater discharge with a focus on a remote wireless monitoring solution. The authors developed an ESP8266 controlled solar-powered buoy-boat

hybrid that measured and recorded dissolved oxygen (DO), pH, turbidity, and temperature in real-time and uploaded the data to Firebase for real-time viewing. Field-testing was conducted across four locations and showed reliable WLAN communication with functional readings across all sensors and enough mobility to complete testing. The wireless local area network (WLAN) communication range limited the use of the monitoring system to smaller water bodies or confined areas of larger lakes. The autonomous navigation was not viable and while usable for monitoring, the cleaning of debris was not included with the system. The gap in the research was their ability to scale in communication using LoRa, autonomy, and eventually combining sensing with cleanup.

6. Shamnaz et al. (2023) - Review of Solar Boats for Water-Quality Monitoring
The review emphasized the international need for water-quality monitoring using renewable energy-driven systems--due to reliance on fossil fuel powered boats and limitations in long duration sampling systems. The authors synthesized boat architectures powered by solar energy and summarized sensor configurations for temperature, conductivity, turbidity, and pH. To establish theoretical benefits of solar boats (e.g., inexpensive, abundant energy, long duration) included no experimental prototypes or real-lake validation. The main research gap is integrated solar USVs tested during variable weather, dynamic wave swells (waves), and under real gradients of contaminants.

7. Solar-Powered Water Boat Design for Measurement of Quality or Quantity (2020)
This review examined the feasibility of solar energy as a power source for autonomous surveys boats to monitor user reservoirs and depth measurements. It demonstrates pH monitoring, depth estimation using ultrasonics, and siltation mapping using Computational Fluid Dynamics (CFD) simulations and hydrostatic modeling. The authors provided design concepts and rationale to support the use of a solar-powered monitoring boat, and prefaced that no prototypes or real-field performance were demonstrated. The identified research gap pertaining to this study is verifying the design techniques used in nature-based reservoirs, developing unique dynamic calibrations of systems in natural reservoirs, and developing the interface to a real-time communication system.

8. Aqua Robot for Floating Debris Collection (2019)
This work investigated the rise in floating plastic debris leading to blockages in drainage systems and adverse effects on aquatic systems to develop a low-cost, robotic alternative to a manned cleanup. The authors designed a robot using an Arduino with wiper motors and a conveyor belt to collect floating debris (up to 5 kg). The robot was tested and functions to collect debris from a calm surface. The limitations of work included only being able to be controlled remotely and having no mobility, no environmental sensors, and limited stability in rough water. The research gaps include adding autonomous navigation, environmental (water quality) sensors, and increased mechanical robustness.

9. Solar-Powered Boat for Water-Quality Monitoring (2024)
This study has developed a buoy-format solar boat that can measure dissolved oxygen (DO), pH, water temperature, and turbidity simultaneously across many locations and be controlled via smartphone with Blynk IoT . The buoy can support a payload of up to 52 kg and has a maximum speed of 40 km/h. Users could view a real-time dashboard of the data streaming to Firebase. Overall, the study found the boat to be very practical and highly mobile, but with limited communication range, and dependent on Wi-Fi infrastructure. The research gap lies in autonomous navigation and long-distance, low-power IoT communication.

10. AquaFeL-PSO (2022) - Path-Planning & Federated Learning for Water Sensing
This solution addressed the inefficiencies of water-sampling missions in traditional ASVs, proposing an informative path planner using PSO, which was then enhanced with both Gaussian Processes, and Federated Learning for environmental mapping with multiple ASVs. Simulated environment missions involved a 14% improvement in the accuracy of the pollution-zone model, as well as a nearly 4000% improvement in peak detection accuracy over classical PSO approaches. However, as with many ASV theoretical models, these experiments did not include real

ASVs, handling debris, or collecting data with real sensors. The original research is still lacking deployment in a real water body, sensor calibrations, or whether the approach could use lightweight robotic boats for deployment.

11. Chang et al. (2021) – Multi-Function USV (Obstacle Avoidance + Sensing + Cleaning)
In this paper, Chang et al. explored the fragmented functional classification within designing USVs. Hence, the authors revealed that most of the designs have a focus on one of the following three aspects: sensing, avoidance of obstacles, or collection of debris. The authors developed and tested a multi-functional USV that uses ultrasonic sensors for obstacle avoidance and pH sensor, water sample collectors, and a vision-based garbage collection system. The testing showed up to 100% detection within a ±30° vision cone, and 95% collection efficiency (0°–15° orientation). The multi-functional USV exhibited several limitations (e.g., insufficient autonomous navigation for a long duration, insufficient multi-parameters sensors systems, and comprehensive energy management analyze systems or methods). Areas for improvement included testing of solar panels, autonomous intelligent vehicle research, and studies involving real lakes.

12. Elkolali and others (2023) - Low-Cost Solar/Wave Powered USV
This study addressed the high operating cost of current solar or wave powered uncrewed surface vehicles (USVs), such as the Wave Glider SV3, and designed a lightweight, lower cost alternative for coastal observations. The authors developed a 1.2-m multihull USV with solar panels, an underwater flapping-wing propulsion unit, and a winch for retrieval capabilities. The USV could accommodate sensors to measure dissolved oxygen, pH, salinity, and temperature. The authors built the design to be manufacturable in terms of using fiberglass hulls and PVC frames. Although the potential to advance observation capabilities was promising, there remains a dearth of evidence from field testing, articulated analysis of sensor performance, and verification of water-quality measurements from laboratory to field. Notably, the research gap includes full integration of sensors, monitoring for energy-autonomy, and testing in real-sea conditions.

Methodology
The research involved the conception, fabrication, and experimental testing of a solar energy powered, IoT-enabled aquatic drone for in-situ environmental measurements and trash collection of surface water bodies. The methodology encompasses hardware and software designs, the integration of sensors and actuators, field testing, and performance evaluation.

System Design and Fabrication: A robot prototype was developed using CAD software design, and the final physical structure was developed using a 3D printer, to ensure that the robot is light and modular in its construction. The main platform of the prototype as shown in the Fig[1] is equipped with -

- A solar panel (20 W, Vmp 18 V typical), for sustainable cleaning.
- A Li-ion battery (12.6 V, 1800 mAh), for onboard energy storage.
- An ESP32 microcontroller, for data acquisition, computing, and wireless communications.
- Sensors to measure real-time parameters: DHT11 (air temperature, humidity), DS18B20 (water temperature), pH sensor, and a turbidity sensor that denote water quality.
- Two continuous servo motors, for propulsion and directional control.
- A debris removal mechanism with two cleaning belts.

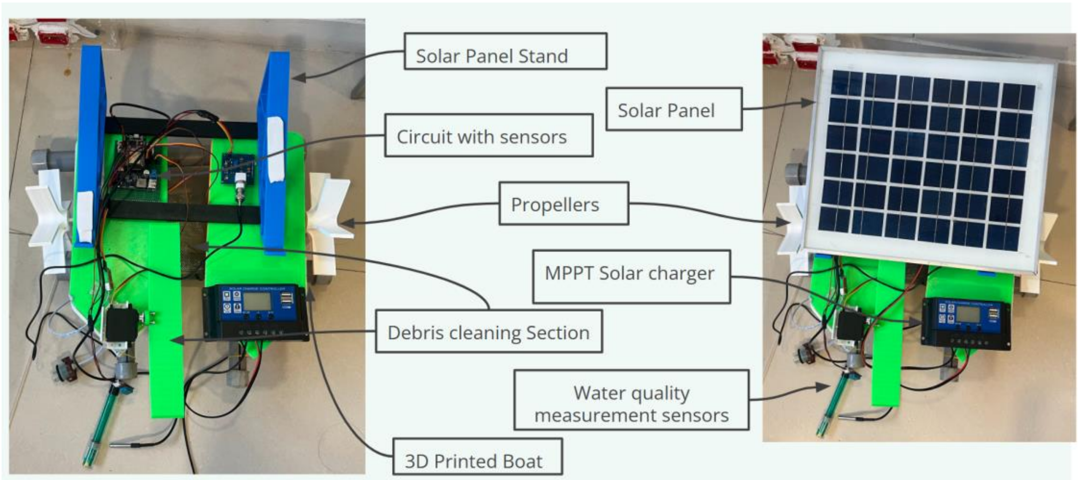
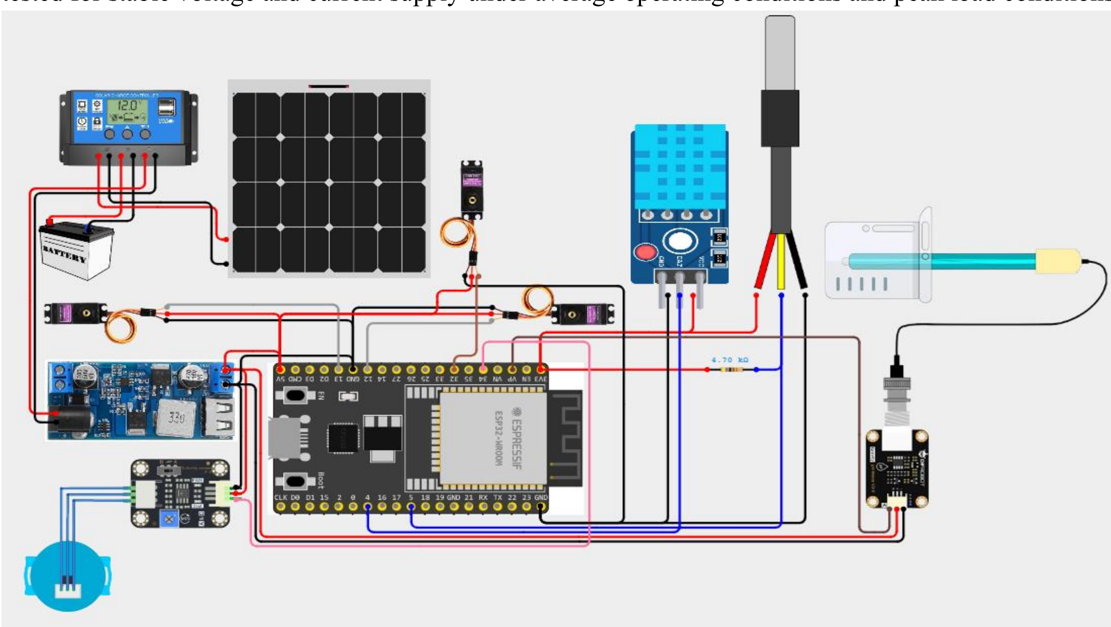


Fig [1]: Physical Structure of the prototype

Integration and Circuit Design: The power subsystem consisted of a solar charge controller and MPPT circuitry to maximize charging efficiency (90-95%). A buck converter was utilized to regulate a voltage supply (12V-5V) to the microcontroller and sensors. The complete circuit as shown in the Fig[2] was assembled as a schematic design and tested for stable voltage and current supply under average operating conditions and peak load conditions.



Fig[2]: Circuit diagram of the complete prototype

Control Systems and Data Display: Remote navigation and operation were established utilizing a Wi-Fi dashboard, as shown in Figure [3], that allowed the operator to

- Steer the robot (forward, backward, left, right) and engage the cleaning system remotely.
- Display/monitor live sensor data (for example, water quality parameters, etc.) using the IoT dashboard to even do spatial and temporal mapping of water conditions.

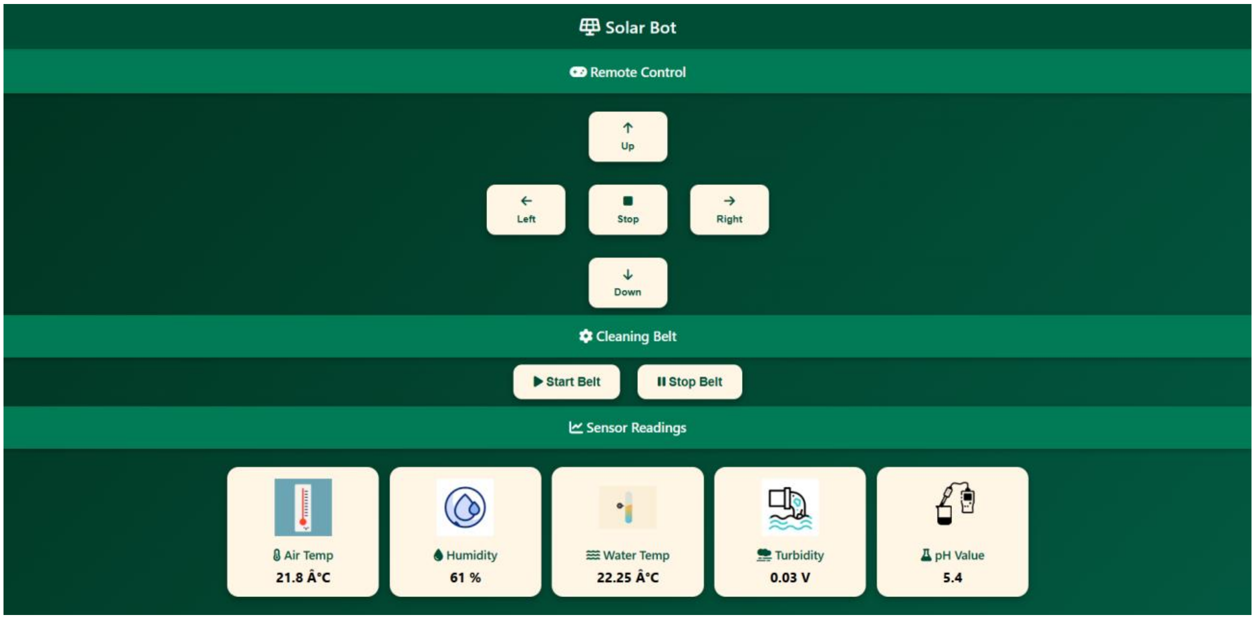


Fig. [3] Dashboard for system control and data display

Experimental Implementation and Processes: The robot was tested in a controlled aquatic environment. The experimental processes consisted of

- Continuous solar charging of the robot during daylight hours, with energy flows monitored to ensure sustainable operations.
- Periodic navigation along prescribed paths for debris collection.
- Recording of water quality metrics (for example, air/water temperature, turbidity, pH) at designated locations in the water and at intervals over multiple trials.
- Data logging over multiple days to determine real-world function, battery performance, and sensor performance in the field.

Fig[4] MPPT Solar charge controller charging the battery

Results and Discussions

The solar-powered floating bot was successfully fabricated, deployed, and validated in field conditions. The following results were recorded during testing and operational runs.

Parameter	Measured Value / Range	Notes
Solar Panel Power	20 W peak	Provides primary energy for sustainable operation
Battery Capacity	12.6 V, 1800 mAh	Supports operation during low sunlight or night

Daily Usable Energy	~72 Wh	After system efficiency and charging losses accounted
Energy Surplus	~14 Wh/day	After 2 h cruising and 22 h idle monitoring load
Cruising Time on Battery	~2.6 hours	Supports extended navigation without solar input
Idle Monitoring Time	~9 hours	Continuous data collection during non-cruising periods
Water Temperature	22.25°C to 28.5°C	Validated sensor readings in deployment
Air Temperature	~21.8°C	Environmental parameter monitoring
Humidity	~61%	Environmental parameter monitoring
Turbidity	0.03 to 0.11 V (low values)	Indicates relatively clear water
pH Value	5.4 to 5.81	Slightly acidic, typical for studied water bodies
Debris Collection	Effective debris removal	Via dual cleaning belts with remote control
IoT Dashboard	Real-time control & monitoring	Remote navigation and environmental data visualization

System Performance and Functionality: The solar energy subsystem, with a 20 W solar panel and Li-ion battery, consistently supplied enough power for both continuous water monitoring and short cruising periods.

- On typical sunny days (4.5 peak sun hours), the panel delivered approximately 72 Wh of usable energy daily, resulting in a daily energy surplus of about 14 Wh even after accounting for all operational and standby loads. The robot could cruise for up to 2.6 hours on battery alone, supporting extended idle monitoring for over 9 hours without solar input.
- MPPT charge controller and efficient power conversion enabled stable operations with battery depths of discharge maintained within safe margins, optimizing battery health and longevity.

Water Quality Monitoring: Real-time sensor readings captured both air and water temperatures, turbidity, and pH in multiple deployment sessions. Sample sensor outputs included:

- Air temperature: 21.8°C, Humidity: 61%
- Water temperature: 22.25°C–28.5°C (documented range)
- Turbidity: 0.03–0.11 V (low, indicating relatively clear water)
- pH values: 5.4–5.81 (slightly acidic, typical for urban water bodies).

Operational Control and Data Visualization:

- The IoT-enabled dashboard reliably facilitated remote navigation (forward, backward, left, right), real-time sensor visualization, and remote activation of the cleaning belt system.
- Debris collection was performed with minimal manual intervention, validating the feasibility of automated water surface cleaning.

Overall Effectiveness: The robot proved capable of providing both effective autonomous water quality monitoring and surface debris removal using renewable energy. Real-world trials indicated robust system reliability and confirmed the model's suitability for scalable environmental remediation in small to medium water bodies.

Conclusion

The solar-powered aquatic robot, created through this project, demonstrates the practicality and efficacy of merging renewable energy, IoT sensing, and automation for aquatic ecosystem monitoring and remediation. While operating in real-world settings, it successfully performed continuous water quality logging of temperature, pH, and turbidity, and effectively captured floating debris, using its two belt cleaning system. The robot was energy autonomous by design, allowing it to operate daily and remotely monitor without external power sources. The IoT dashboard allowed for remote control, an intuitive user interface, and visualization in real-time to instill confidence in operational reliability and ease of use for autonomous deployment in small to medium-sized bodies of water. This project demonstrates that sustainable, low-cost, scalable robotics solutions can be applied to problems related to water pollution, decrease intervention, and allow data-driven water management. Additionally, the proposed method provides a solid foundation for intelligent and distributed environmental monitoring systems, and could be further developed for greater autonomy, resilience capabilities, and AI-enhanced analytics integration in the future. Future enhancements can be based on improving the robot's autonomy and functionality with advanced obstacle avoidance, GPS-based navigation, and AI-based classification systems, all to keep aquatic organisms free from harm. Similarly, adding higher-efficiency solar panels and improved battery technologies can help promote extended operational time and environmental coverage. Sensor networks, with shared communication and integration with edge-computing, can help promote coordinated, large-scale aquatic monitoring and data processing for intelligent, real-time water management and automated environmental remediation.

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