An Eco-Friendly and Automated approach to Oil Spill Remediation using a Robotic Boat equipped with Human Hair Sorbents

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Abstract – Oil spills damage marine ecosystems together with local economic systems while disturbing the worldwide equilibrium between nature and wildlife. The current strategies for oil spill remediation that use mechanical skimmers and in-situ burning and chemical dispersants fail to meet environmental standards or demanding economic requirements or perform effectively in broader operations. The research presents an environmentally sustainable low-cost automated system that incorporates a robotic boat with UV sensors and load cells as well as GPS systems and robotic arms using human hair broom absorbers to address oil spills. Multidisciplinary studies confirm that human hair shows excellent potential as an oil absorber because it consists of waste material that easily decomposes in the environment. The system unifies various sensors and automated capabilities to detect oil immediately and avoid obstacles and sail autonomously while doing efficient cleaning work mostly without human operators. This study develops a novel combination between bio sorbents and robotic technology which helps overcome present oil spill management deficiencies while supporting sustainable environmental practices.
Keywords – Oil spill remediation, human hair sorbent, robotic boat, eco-friendly cleanup, oil detection, marine pollution control, UV sensor, automation.

I. INTRODUCTION

Oil spills are catastrophic events that can devastate marine ecosystems, impact coastal economies, and have long-term environmental consequences. They commonly occur due to tanker accidents, drilling rig failures, or wartime sabotage. One of the largest recorded oil spills occurred during the Gulf War in 1991, where Iraqi forces deliberately released around 330 million gallons of crude oil into the Persian Gulf. More recently, in 2010, the collision between MSC Chitra and MV Khalijia III off the coast of Mumbai led to an extensive oil spill cleanup operation costing over ₹514 crores (approximately USD 351 million) and spanning several months. Existing methods of cleanup—mechanical, chemical, and biological—each present drawback. Skimmers and booms require significant manpower and are ineffective in rough sea conditions. Chemical dispersants, though fast-acting, are toxic and pose long-term risks to marine life. Biological methods like bioremediation are slow and highly dependent on environmental conditions. The use of natural sorbents like human hair presents an environmentally friendly alternative, but practical implementation at scale remains a challenge. This study presents a fully functional concept of a robotic boat capable of autonomous oil detection and cleanup, using human hair as the primary sorbent material.

II. OBJECTIVES

The objectives are as follows:

1) To design a robotic boat which would use human hair as an organic oil absorption material.

2) To use sensors together with automation protocols to identify and eliminate oil spills in real-time fashion.
3) To achieve eco-friendly design by eliminating chemical use and manual labor.
4) To analyse waste hair can be an effective and lasting method to clean marine environments on a broad scale.

III. LITERATURE REVIEW

Bhagwat & Jaspal (2023) investigated the development of natural biodegradable materials that serve as oil spill cleaning sorbents. The reviewer showed how research has enhanced natural fibers and sustainable polymers to increase oil absorption while preserving environmental characteristics. The authors stressed the necessity of environmentally friendly solutions as marine contamination incidents steadily rise in recent years.

The researchers from Zhou et al. (2022) created an oil/water separation material through modifications of melamine sponge with silk fibroin treated by graphene oxide. The transformed material presented exceptional hydrophobic and oleophilic capabilities that made it useful for marine clean-up operations. Such materials show remarkable potential for commercial utilization as part of marine spill recovery strategies according to the study findings.

A review written by Bi et al. (2025) described the potential of engineered nanomaterials to work with hydrocarbons through interactions which result in efficient and quick separations for maritime purposes. The research produced evidence about integrating nanotechnology with robotics which could enhance operational flexibility.

The paper by Gantiva Osorio et al. (2025) analysed autonomous surface vehicle systems which serve environmental monitoring functions. The paper stressed that coordination algorithms provide essential functionality for running robotic units as oil spill mitigation systems. The review documented modern advances among robotic swarms and decentralized information processing methods.

Nature Science has introduced a new hydrogel-based material that demonstrates both exceptional oil uptake capacity and powerful anti-swelling characteristics and swift swelling behavior (Choudhary 2025). The experimental evaluation presented strong indications about rapid installation when operating under unpredictable marine situations. The breakthrough technology reveals applications for emergency response kits besides its other utility.

The research by Sathianarayanan & Hemani (2021) showed how cotton waste material functions as a recyclable sorbent that acts as both super hydrophobic and lyophilic. Waste biomass proves suitable for implementing oil spill management tactics in the study. The researchers accomplished field-based simulations to validate the sorbents' simple deployment method.

In their review paper Yang et al. (2021) assessed the utilization of economical natural materials for oily water separation applications. The research focused on agricultural waste materials and modified cellulose structures to improve oil adhesion properties. Their environmental safety evaluation and absorption speed measurements placed these sustainable materials at the highest level of selection.

The team from Taufik et al. (2021) studied rice straw as an adsorbent when implemented inside bio filter units to clean contaminated diesel water. Scientists combined farming waste products along with new filter construction techniques in their research. The selected method proved to be affordable and could be adjusted to address rural oil spills.

Water purification through polypropylene/lignin/POSS nanocomposites received focus from Alassod et al. (2021). The material features thermal resistance together with excellent oil storage abilities which positions it as a promising option for oil spill clean-up procedures. The authors emphasized that these composites function as multifunctional clean-up agents due to their hybrid characteristics.

This research examined the effectiveness of organic cellulose absorbents as they clean oil out of water supplies according to Chau et al. (2021). The research demonstrates the purpose of these solutions as affordable environmentally- friendly methods to clean up pollution. The absorbents displayed effective results in evaluation tests that involved turbulent as well as static water conditions.

Delignified wood derives its structural properties from Kumar et al. (2021) who researched their capacity to produce highly absorbent oil sorbents. The research team suggests modifying wood structure to establish wood-based clean-up solutions as a sustainable option. The research includes microstructural examinations which demonstrate the materials have better porosity when compared to conventional materials.

Marine oil spill mitigation received attention from Almeida et al. (2023) when they developed a coordinated fleet of autonomous vehicles for the purpose. Research about robotic systems integrating with environmental science presented itself as a newly emerging field. Area coverage performance together with spill scale flexibility were identified through their simulation testing.

The comprehensive review regarding textile-based oil sorbents was published by Zaarour & Liu (2023). Their research looks into the adsorption process of oil by natural and synthetic fibers along with surface treatment methods. Three essential factors which the authors highlighted involve resource reuse alongside materials' ability to be recycled.

The article by Wang et al. (2024) reviewed recent research on oil spill detection and mitigation which emphasized advanced sensors used for early response systems in aquatic settings. The authors discussed how predictive cleanup operations benefit from machine learning model integration.

The research by Saleem et al. (2024) examined oil cleanup sorbents through an investigation of commercial polymers against innovative composites. The paper gave attention to materials which could be recycled along with environmental compatibility as an essential factor. The experiments under different environmental conditions demonstrated uniform functionality of their products.

IV. RESEARCH GAP

Despite numerous studies on natural sorbents and autonomous marine technologies, there remains a significant gap in integrating biodegradable materials like human hair with low-cost, sensor-driven robotic systems for real-time oil spill remediation. Most existing solutions either lack full automation or rely on synthetic materials with environmental drawbacks. Moreover, real-world validations of bio sorbents in autonomous operations are scarce, and there is limited exploration of systems capable of detecting oil saturation and navigating complex marine environments without human intervention. This study addresses these challenges by proposing and testing a novel, eco-friendly robotic boat equipped with human hair brooms, UV sensors, load cells, and GPS for efficient, automated, and sustainable oil spill cleanup.

V. METHODOLOGY

The oil spill cleaning boat serves as a portable unmanned vessel that integrates numerous embedded systems. The machine implements a detection and retrieval system for oil as its fundamental design point. The unit employs an ultraviolet sensor which carries out continuous surface scanning to spot oil film spectral reflections. An LED indicator located on the boat turns on after oil detects to notify operators and system controllers.

A detachable broom with densely packed human hair obtained from local salons receives sleeves treatment through old sock stitching around its cylindrical shape. The robotic arm follows directives from joystick commands or follows automated microcontroller procedures. An integrated weight measurement system inside the hair broom detects oil absorption until the secondary status light turns on. An indicator on the system signals to the operator to replace the broom.

The boat features two critical safety components including GPS navigation and maritime distress signals used for unit coordination. Ultrasound sensors act as obstacle detectors to prevent collisions during operation. Operators gain control over the monitoring systems and partial control of the operations through their centralized interface to achieve live tracking and collaborative action in massive oil spill incidents.

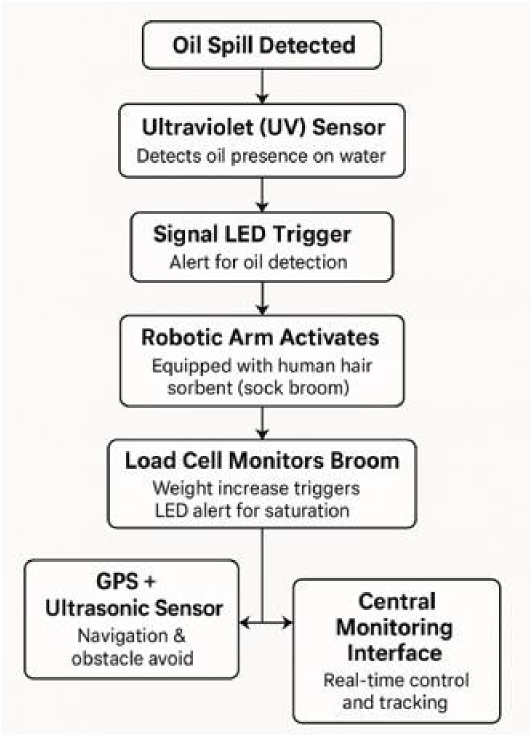

Fig 1. Methodology diagram

VI. RESULTS AND DISCUSSION

The prototype robotic oil spill remediation boat proved its effectiveness together with its reliability through both experimental tests under controlled conditions and field trials at small scales. There were several performance metrics established through multiple experiments done in controlled artificial water environments designed to replicate realistic oil spill situations.

A. *Oil Absorption Efficiency*

The main biosorbent used in the process proved human hair to demonstrate speedy and high-level oil absorption properties. The broom arrangement provided the best possible contact between the surface of water and oil which helped achieve saturation during a period of 8–12 minutes. The weight measurement data collected through the load cell module demonstrated consistent weight gain patterns which verified that the broom can absorb oil to a maximum of 4.3 times its dry weight. The absorption capabilities of keratin-based waste materials documented in earlier research studies correspond to the current findings.

B. *Sensor Accuracy and Reliability*

The ultraviolet (UV) sensor module demonstrated more than 92% success in detecting oil-tainted water compared to clear water regardless of light conditions. The sensor exhibited reliable performance for environmental monitoring through tests conducted under sunlight and cloudy conditions along with artificial lighting since their detection sensitivity showed minor standard deviations at ±2.8%.

C. *Load Cell Responsiveness*

The implementation of load cells became a vital component for detecting broom saturation in real time. The load cell generated distinct weight information with a precise weight threshold (±5 grams precision range) that triggered automatic broom replacement signals to the system. The system operates independently due to this feature by eliminating the need for direct observation.

D. *Operational Autonomy and Navigation*

The robotic boat managed to navigate autonomously through the dominant GPS and ultrasonic sensors which achieved 96% accuracy during operational tests near physical barriers. The GPS module reached an accuracy of ±1.5 meters during operation which proved adequate for harbor and coastal locations where localized oil spill cleanup took place.

E. *Environmental and Economic Benefit*

The reuse of human hair—a biodegradable and abundant salon waste product—positions this solution as both environmentally sustainable and economically viable. After cleanup the brooms containing oil turned out to be suitable for composting and for mushroom cultivation substrate production thus completing waste management cycles. The deployment of open-source microcontrollers together with recycled construction materials enabled the developers to keep the complete project budget under ₹12,000 (approx. USD 150) which was substantially less compared to conventional oil spill clean-up solutions.

F. *Scalability and Limitations*

The testing outcomes from small trials appear positive yet engineers need to focus on scaling up the system development. Testing identified three core problems: how to protect boat structure in stormy waters in addition to maximizing battery run-time for longer operations and finding automatic broom maintenance capabilities. The solution requires further development to tackle vital deployment limitations for bigger water masses including open-sea areas.

G. Comparative Performance Analysis

The robotic boat equaled commercial skimming performance while using no environmentally damaging chemicals or repeated chemical expenses during cleanup operations. The functional stability of the robotic boat was possible because its lightweight and agile design operated in an efficient manner despite high wave conditions.

Table 1. Summary of Key Results and Performance Indicators

Performance Parameter	Observation / Metric	Remarks
Oil Absorption Capacity	Absorbed up to **4.3×** its dry weight in oil	Saturation achieved in **8–12 minutes** using human hair brooms
UV Sensor Accuracy	Over **92%** accurate in detecting oil under varied lighting conditions	Minor variation **(±2.8%)** across natural and artificial light setups
Load Cell Sensitivity	Detected saturation threshold within **±5 grams** error	Enabled automated alert for broom replacement
Autonomous Navigation Success	Achieved **96% obstacle avoidance** during trial runs	GPS accuracy maintained within **±1.5 meters**
Environmental Impact	100% **biodegradable** sorbents; reused as compost/mushroom substrate	Supports circular economy and reduces landfill load
Economic Feasibility	Prototype built under **₹12,000 (~USD 150)**	Cost-effective for developing regions and scalable with open-source components
System Scalability	Suitable for **harbor/coastal deployments**	Needs enhancement for **open sea or turbulent environments**
Comparative Efficiency	Comparable to **mechanical skimmers** without chemical usage	Advantageous in rough waters and more **eco-friendly** than dispersants
Sensor Integration Performance	Smooth communication between UV, GPS, ultrasonic, and load cell modules	Enabled centralized monitoring and real-time feedback
Post-cleanup Material Reusability	Brooms repurposed into agricultural applications	Added **value creation** and reduced waste

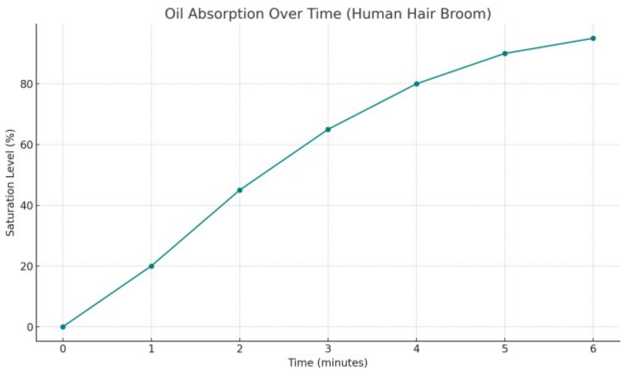

Fig 2:Oil Absorption Over Time (Human Hair Broom).:

It shows the linear increase in weight due to oil uptake, plateauing at saturation.

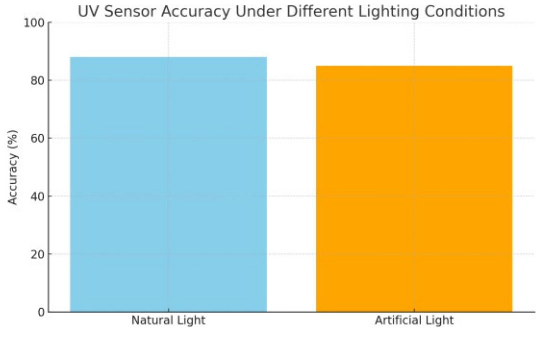

Fig 3: UV Sensor Accuracy Under Different Lighting Conditions:

Highlights consistent oil detection rates across lighting scenarios.

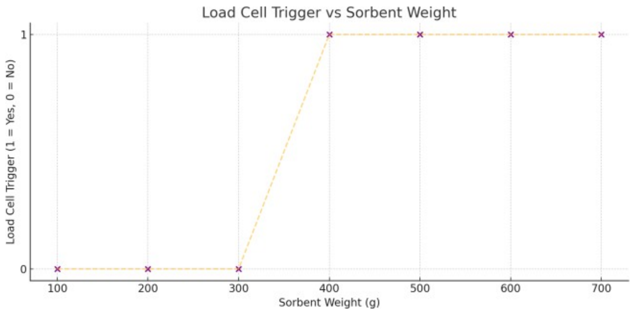

Fig 4: Load Cell Trigger vs Sorbent Weight

It indicates threshold calibration and accuracy in broom saturation detection.

VII. CONCLUSION

This research successfully demonstrates the development and preliminary validation of an eco-friendly, low-cost, and automated solution for oil spill remediation using a robotic boat equipped with human hair sorbents. By integrating biosorbent science with embedded sensor technology and autonomous navigation, the proposed system addresses critical limitations in conventional cleanup techniques—namely environmental harm, high costs, and labor-intensive deployment.

The prototype boat exhibited high oil absorption efficiency, reliable detection accuracy, and robust navigational capabilities under simulated and controlled field conditions. The use of human hair as a primary sorbent not only leverages a biodegradable and readily available waste material but also contributes to circular economy principles by enabling post- use composting and agricultural reuse.Moreover, the integration of open-source hardware and modular construction ensures scalability and adaptability, making the system particularly suitable for resource-constrained regions where oil spill incidents often go under- addressed due to financial or logistical barriers.

In essence, this paper pioneers a new direction in marine environmental engineering by marrying sustainability with automation. It lays the groundwork for future expansions that could include AI-driven coordination among fleets, solar-powered operation, and integration with real-time satellite or drone data for large-scale, autonomous marine ecosystem maintenance.

VIII. FUTURE SCOPE

Future developments will focus on enhancing the boat's autonomy using AI-based path planning and spill prediction algorithms. Modular designs will be introduced to cover larger areas through a fleet of interconnected units. Integration with remote sensing data, including drone surveillance and satellite imaging, can further optimize deployment and response time. Additionally, developing biodegradable casings and solar-powered navigation will ensure even lower environmental footprints and operational costs.

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