Microplastics in water, Detection and Mitigation strategies

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Abstract

Microplastic pollution presents an escalating environmental challenge in our water ecosystems. These tiny particles(less than 5mm)have invaded waterways worldwide, threatening aquatic organisms through ingestion and toxic contamination, with conventional removal methods proving insufficient. Recent advancements in detection technologies offer promising solutions. Laboratory spectroscopy techniques (FTIR and Raman) provide precise identification but remain impractical for field deployment due to cost and complexity constraints. Image processing systems show more significant potential for detection despite limitations in turbid conditions. Our prototype autonomous collection robot employs a conveyor mechanism with image recognition capabilities for surface microplastic retrieval. While demonstrating promise, this system faces several challenges: limited to surface collection, vulnerability to environmental conditions, short operational duration (4-hour battery life), and detection difficulties in murky water. Alternative approaches, including chemical, magnetic, and acoustic separation methods, exist but encounter significant barriers to practical implementation at scale. Despite current constraints, autonomous robotic systems help address this crisis, particularly for floating debris in inaccessible waters. Future development should focus on enhancing detection reliability, expanding collection capabilities, improving operational longevity, and ensuring ecological selectivity.

Keywords: Microplastic pollution, Aquatic ecosystems, Detection methods, Removal systems, Spectroscopy, FTIR, Raman, Image processing, Machine learning, Autonomous robots, Conveyor mechanism, Turbidity, Battery life, Chemical separation, Magnetic separation, Acoustic separation, Environmental challenges, Operational limitations, Ecological selectivity

1. Introduction

Microplastics are small plastic pieces, typically less than 5 mm in size. They originate from both primary and secondary sources. Primary microplastics include microbeads found in cosmetic and medical products, which cause severe damage to the digestive systems of aquatic animals as they are often mistaken for food. This potentially introduces toxins into the food chain, thereby damaging ecosystems. In response, several global actions have been taken against microbeads.

Secondary microplastics, on the other hand, are formed by the breakdown of larger plastic materials due to environmental factors such as sunlight, wind, and water. Despite regulations on microbeads, other major sources of microplastics continue to draw global attention. Over the past few decades, the amount of anthropogenic litter in aquatic environments has significantly increased, with approximately 60–80% being plastic waste.[1]

2. Literature Review

Microplastics, ubiquitous environmental contaminants originating from the degradation of larger plastic debris and the direct release of small plastic particles, represent a growing global concern [6]. These particles exhibit remarkable persistence in various environmental matrices, enduring for extended periods and progressively fragmenting into smaller, sub-micron sized particles [6]. This fragmentation significantly complicates remediation efforts. The pervasive nature of microplastics is evidenced by their detection across diverse environmental compartments, including drinking water sources, commercially harvested seafood, table salt, and even atmospheric aerosols, indicating multiple pathways for human exposure [6].

The potential ramifications of microplastic exposure for human health are substantial and multifaceted. Inhalation of airborne microplastics can lead to their accumulation within the pulmonary system, potentially causing respiratory distress, persistent coughing, and exacerbating pre-existing conditions such as asthma and bronchitis [7]. Furthermore, plastic products often contain a cocktail of chemical additives, including endocrine-disrupting compounds like bisphenol A (BPA), phthalates, and various flame retardants [7]. These substances can leach from the plastic matrix and interfere with the body's hormonal regulation systems, potentially contributing to the development of cardiovascular diseases, reproductive complications, and immune system dysregulation [7]. Studies have indicated a possible link between the consumption of microplastic-contaminated products and an increased risk of certain cancers [7]. Recent research has provided direct evidence of microplastic translocation within the human body, with studies detecting microplastic concentrations in vital organs such as the liver, kidneys, and even the brain, although the long-term physiological consequences of this internal accumulation remain under investigation [8].

Beyond direct human health impacts, microplastic pollution

contributes to broader environmental degradation. The process of plastic degradation itself releases potent greenhouse gases, notably methane (CH_4) and ethylene (C_2H_4), thereby contributing to anthropogenic climate change [7]. Recognizing the environmental threat, legislative actions have been initiated globally. The United States implemented the Microbead-Free Waters Act in 2015, prohibiting the inclusion of plastic microbeads in rinse-off cosmetic products [9]. Similar regulatory measures targeting microbeads in personal care items have been adopted by several other nations, including Canada, France, New Zealand, Sweden, and Taiwan [9].

In India, the challenge of plastic pollution is particularly acute. Significant plastic contamination plagues the nation's river systems, creating a high potential for microplastic infiltration into drinking water supplies, posing consequent health risks to the population [10]. Elevated levels of microplastics have also been documented in Indian marine environments, such as the Arabian Sea and the Bay of Bengal, endangering aquatic ecosystems [10]. Microplastic contamination extends to terrestrial ecosystems as well; the use of contaminated water for irrigation introduces microplastics into agricultural soils [11]. This accumulation can detrimentally affect soil fertility, disrupt the delicate microbial balance essential for nutrient cycling and plant health, and ultimately reduce agricultural productivity [11]. In response to the escalating plastic waste crisis, India implemented a nationwide ban on specific single-use plastic items, including cutlery, straws, and certain packaging films, effective from July 2022, aiming to curb plastic consumption and mitigate the formation of secondary microplastics [11].

The economic consequences of microplastic pollution are also significant, particularly for regions reliant on environmental resources. Coastal areas popular for tourism, such as Goa and Kerala in India, face substantial challenges from plastic pollution, including microplastics, which detracts from their natural appeal and can negatively impact state economies and the livelihoods of local communities dependent on tourism revenue [12]. Furthermore, states like Andhra Pradesh, a leading producer of seafood and aquaculture products in India, face economic vulnerability due to microplastic contamination [13]. The contamination of seafood stocks not only raises public health concerns but can also lead to significant economic losses for the fisheries and aquaculture sectors, affecting the large population whose livelihoods depend on these marine resources [13]. The pervasive presence and multifaceted impacts of microplastics underscore the urgent need for continued research, comprehensive mitigation strategies, and robust policy interventions.

3. Materials and Methods

3.1. Detection Methods

Several methodologies are employed for detecting and characterizing microplastics in environmental samples. These include spectroscopic, imaging, chemical, and advanced techniques.

3.1.1. Spectroscopic Methods

Spectroscopic analyses provide detailed information about the polymer composition of microplastics:

- **FTIR (Fourier Transform Infrared) Spectroscopy**: Identifies polymer types by measuring infrared light absorption patterns unique to different plastic compounds
- **Raman Spectroscopy**: Measures scattered light to identify polymers and provides higher spatial resolution than FTIR
- **Pyrolysis-GC/MS**: Thermally degrades plastics and analyzes the resulting compounds to identify polymer types

3.1.2. Chemical Methods

Chemical procedures facilitate separation and isolation of microplastics:

- **Density Separation**: Exploits different densities of plastics and environmental matrices
- **Oxidation/Digestion**: Removes organic matter while preserving plastics
- **Staining Techniques**: Chemical stains that selectively attach to polymers

3.1.3. Advanced Techniques

Novel approaches enhance detection capabilities:

- **Thermal Extraction Desorption GC/MS**: Identifies plastic types based on their thermal properties
- **Flow Cytometry**: Rapid counting and sorting of microplastics
- **Hyperspectral Imaging**: Combines imaging with spectroscopy for spatial and compositional data

3.2. Experimental Approach

In this study, we focused on developing an microplastic detection system utilizing image processing techniques. Our conceptual model integrates a camera system, image processing algorithms, and an Arduino-controlled extraction mechanism. Figure 1 illustrates the proposed system architecture, highlighting the workflow from image acquisition to microplastic Removal.

Image processing involves a series of operations on digital images to improve their quality or to extract important features. The significant steps are:

Image Acquisition: Capturing images using cameras or sensors

Preprocessing: Enhancing image quality by minimizing noise, modifying contrast, or correcting distortions.

Segmentation: Dividing an image into meaningful regions (e.g., separating particles from the water background).

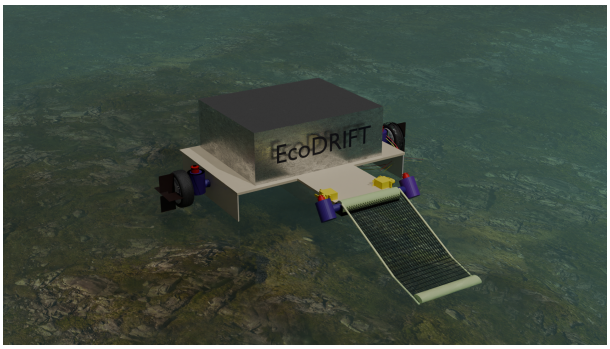

Figure 1: 3D model of the microplastic mitigation model using image processing technique

Feature Extraction: Identifying and measuring characteristics such as shape, size, color, and texture.

Classification and Analysis: Using the extracted features to classify objects (for example, distinguishing microplastics from other particles), often with computational algorithms.

3.2.1. Image Processing for MicroPlastic Detection

Image Acquisition:. A high-resolution camera or specialized imaging sensor captures detailed images of water samples. Ensuring a controlled environment with consistent lighting will minimize the variations or distortions that could interfere with detecting microplastic particles. UV or fluorescence-based imaging may improve contrast between microplastics and other particles.

PreProcessing:. Filterssuch as Gaussian blur or median filtersare applied to smooth out random variations or "noise" in the image. This step helps to remove unwanted speckles or distortions that might hide microplastics. The brightness and contrast of the images are adjusted so that the microplastics stand out more prominently against the background. This step improves the visibility of the particles. The next step is normalization, where we standardize the image scale and intensity to create uniform conditions, reducing variability across different water samples.

Segmentation. A specific brightness or color value is set as a threshold. Pixels within this range are separated from the rest, helping to isolate potential microplastic particles from the water background. Algorithms like the Canny edge detector are used to trace the boundaries of objects. By outlining these edges, the system can more accurately define the shape of each potential microplastic particle. Techniques such as dilation (which expands object boundaries) and erosion (which shrinks them) are applied to refine the segmented regions. These operations help remove minor artifacts and connect fragmented parts of the particles, resulting in clearer object outlines.

Feature Extraction. Once objects are segmented, the contours of each detected particle are measured. This analysis determines whether the shape matches typical microplastic profiles. The dimensions of each particle are calculated to help filter out objects that are either too large or too small to be microplastics. This ensures that only relevant particles are considered. The surface texture and color of each object are analyzed. These characteristics help distinguish microplastics from other particles, such as organic matter or mineral sediments.

Classification. Advanced models, such as Convolutional Neural Networks (CNNs), are trained on labeled datasets (images where microplastics have been marked) to learn what microplastics look like. This training allows the model to recognize microplastics in new images more accurately. The system combines multiple featuresshape, size, texture, and colorto decide whether a detected particle is a microplastic.

Removal of microplastics after detection:. Once microplastics are identified, a command is sent to an Arduino-controlled robot, which makes the conveyor belt move, picks up the microplastic particle, and puts it in a box.

3.2.2. Current Implementation

However, due to resource constraints and practical limitations, the current implementation focuses on detecting and removing microplastics visible to the naked eye (> 1 mm). This approach allows us to evaluate the fundamental principles of microplastic extraction while mitigating the technical challenges associated with high-resolution imaging systems and advanced image processing algorithms. As resources permit, the computational intelligence component and sophisticated image analysis capabilities will be incorporated in future iterations.

3.3. Device Engineering and Implementation

3.3.1. Working principle

The model operates by floating on calm water surfaces, propelled and navigated via Bluetooth-controlled motors managed by an Arduino microcontroller. An inclined conveyor belt collects surface microplastics and water, directing the mixture into a perforated container that drains water while retaining debris. An 11.1V Li-ion battery pack powers the system and provides up to 2.5 hours of operation. This gives a vague idea about how the model works. Figure 4

3.3.2. Electronic Infrastructure

Essential electronic components integrated for optimal device functionality include:

- **Arduino UNO R3 Original**-The authenticated controller developed by Arduino.cc Justification for selecting authentic components over alternatives:
  - Enhanced manufacturing standards with superior component durability.
  - Consistent operational parameters without intermittent disconnections or thermal issues.
  - Comprehensive compatibility with Arduino programming libraries and peripheral components.

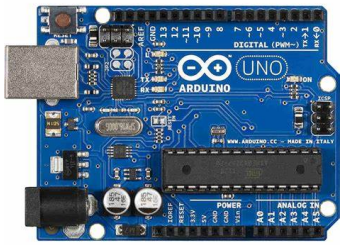

Figure 2: Arduino UNO R3 microcontroller board.

- Streamlined driver integration facilitating immediate functionality with Arduino development environment.

- **HC-05 Communication Module**- Frequently implemented Bluetooth component for wireless interface with microcontroller platforms, including Arduino and Raspberry Pi. The module supports default communication at 9600 baud and facilitates remote control and data transmission applications. Operational parameters include:
  - Data reception from Bluetooth interface for presentation through Serial Monitor.
  - Information transmission from Serial Monitor to Bluetooth module.

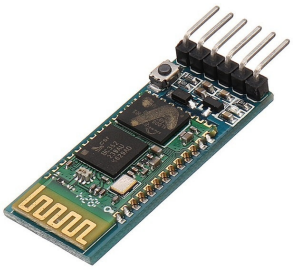

Figure 3: HC-05 Bluetooth communication module.

- **Robodo L298N Motor Controller**- Widely implemented component for DC motor regulation with microcontroller integration. Technical specifications include:
  - Operational voltage range: 5V to 35V.
  - Maximum current capacity: 2A per channel.
  - Dual DC motor control capability or single stepper motor operation.
  - PWM compatibility for variable speed regulation.
  - Bidirectional rotation functionality.
  - Enhanced thermal dissipation during elevated load conditions.

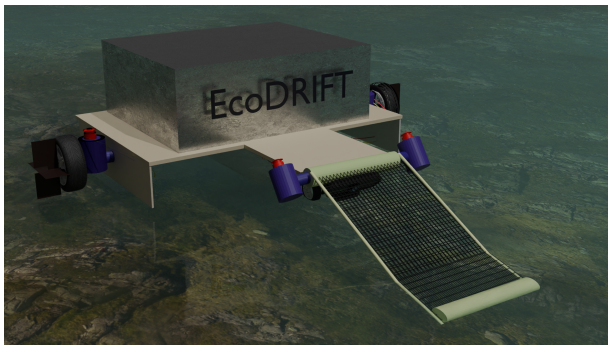

Figure 4: 3D model of the proposed working model

- For the input Power supply: For the proper functioning of the Arduino, a 12V power supply is needed. Instead of alkaline batteries, lithium batteries are preferred for several reasons:
  - Alkaline batteries (1.5V each) require multiple cells in series, which can be bulky.
  - Lithium-ion (Li-ion) and lithium-polymer (Li-Po) batteries provide 3.7V per cell, closer to what Arduino boards need.
  - Lithium batteries store more energy in a smaller size, making them compact and lightweight.
  - Lithium batteries are better for Arduino projects because they offer higher energy density, stable voltage, and rechargeability

  To achieve 12V, a series combination of three 3.7V lithium cells is used ($3 \times 3.7\text{V} = 11.1\text{V}$). A battery holder assembles the cells securely and provides clean terminals. This setup is cost-effective, compact, and efficient.

For the robot's motion, two backend wheels and a small wheel in the middle are used to support and stabilize its motion. Backend wheels are connected to a DC motor (5V), and a motor driver (Robodo L298N Motor Drive) is used to function. DC motors are connected to the motor driver's output channel. The dual H-bridge driver module allows the motor driver to control the speed and direction of two DC motors.

Connection between HC-05 Bluetooth and Arduino: Connected so that the Arduino can receive wireless commands from your phone or another Bluetooth-enabled device. HC-05 is powered through the 5V power supply pin of Arduino. The Transmitter and receiver pins of the Arduino and HC-05 are cross-connected. The TX pin of HC-05 is connected to the RX pin of Arduino to enable HC-05 to send data. Similarly, the TX pin of Arduino is connected to the RX pin of HC-05. However, the Arduino's TX pin is 5V, while HC-05 RX only accepts 3.3V, so we use a voltage divider to avoid damaging the Bluetooth module.

Conveyer belt connections: 2 motors on either side of the PVP Pipe and connected to create a rotational pull of the conveyer belt. These motors are powered directly to the power supply and are controlled by a two-way input switch.

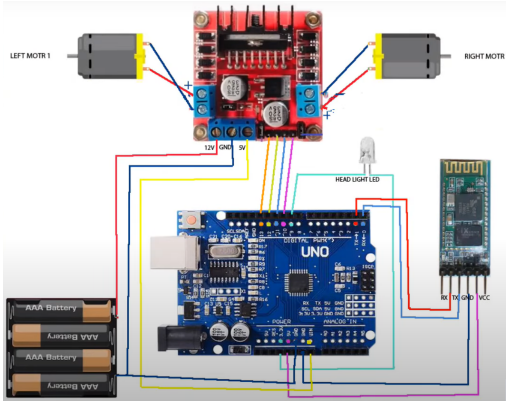

Figure 5: Circuit connections diagram for robot control components.

3.3.3. *Programmatic Implementation for Autonomous Operation*

Algorithm 1 Algorithm for the above Implementation

```
Initialize digital pins for motor control (13, 12, 11, 10)
Establish serial communication at 9600 bps
while true do
    if serial data available then
        Read incoming character
        Display received command
        if command = 'F' then
            Activate forward motion for both motors
        else if command = 'B' then
            Activate reverse motion for both motors
        else if command = 'L' then
            Activate right turn (left motor forward only)
        else if command = 'R' then
            Activate left turn (right motor forward only)
        else if command = 'S' then
            Deactivate all motors
        end if
    end if
    Introduce 100 ms operational delay
end while
```

```
% --- C++ code content ---
char r;

void setup() {
  pinMode(13, OUTPUT); // forward motion of left motor
  pinMode(12, OUTPUT); // reverse motion of left motor
  pinMode(11, OUTPUT); // forward motion of right motor
  pinMode(10, OUTPUT); // reverse motion of right motor
  Serial.begin(9600); // initialize serial at 9600 bps
}

void loop() {
  if (Serial.available()) {
    r = Serial.read();
    Serial.println(r); // Added semicolon
  }

  // Stop previous motion before starting new one
  digitalWrite(10, LOW);
  digitalWrite(11, LOW);
  digitalWrite(12, LOW);
  digitalWrite(13, LOW);

  if (r == 'F') { // Forward
    digitalWrite(13, HIGH);
    digitalWrite(11, HIGH);
  }
  else if (r == 'B') { // Backward
    digitalWrite(12, HIGH);
    digitalWrite(10, HIGH);
  }
  else if (r == 'L') { // Left Turn (Right motor fwd, Left motor off/rev?)
                       // Current: Left OFF, Right FWD = Turns Left
    digitalWrite(13, LOW); // Ensure Left motor FWD is off
    digitalWrite(12, LOW); // Ensure Left motor REV is off
    digitalWrite(11, HIGH); // Right motor FWD ON
    digitalWrite(10, LOW); // Ensure Right motor REV is off
  }
  else if (r == 'R') { // Right Turn (Left motor fwd, Right motor off/rev?)
                       // Current: Left FWD, Right OFF = Turns Right
    digitalWrite(13, HIGH); // Left motor FWD ON
    digitalWrite(12, LOW); // Ensure Left motor REV is off
    digitalWrite(11, LOW); // Ensure Right motor FWD is off
    digitalWrite(10, LOW); // Ensure Right motor REV is off
  }
  else if (r == 'S') { // Stop - Already handled by the code block above
    // All pins set LOW implicitly by the block before the if/else chain
  }

  delay(100); // 100 ms loop delay
}
% --- End C++ code content ---
```

Listing 1: Arduino Implementation Code for Autonomous Navigation

The Arduino microcontroller serves as the central controller for robot locomotion. It interprets directional commands ('F,' 'B,' 'L,' 'R') received wirelessly from a mobile application via the HC-05 Bluetooth module. Based on the received command, the Arduino sends signals to an L298N motor driver powered by 11.1V lithium cells, which manages the two DC motors for forward, backward, or single-motor turning actions. Separately, the conveyor belt mechanism runs continuously once initiated manually using a DPDT switch, a decision made to simplify the electronics and reduce component count.
For readers interested in implementing the original proposed system using image processing for microplastic detection, please refer to Appendix A.

3.3.4. Methodological Rationale

The implementation of mechanical extraction methodology was selected over filtration or chemical intervention approaches following a comprehensive evaluation of operational parameters. This selection was predicated upon significant cost-effectiveness advantages through reduced operational expenditure and extended system longevity. Additionally, the approach facilitates operational continuity without interruption for consumable replacement, a critical consideration for remote deployment scenarios. Furthermore, the mechanical extraction system demonstrates exceptional adaptability across diverse aquatic environments while maintaining consistent remediation efficacy. This scalable solution balances implementation feasibility with performance metrics across varied deployment contexts.

4. Results and Discussion

This section presents the findings from the Fourier-Transform Infrared (FTIR) spectroscopic analysis of water samples, evaluates the performance and design considerations of the developed robotic system for microplastic collection, and discusses the implications of public perception regarding microplastic pollution based on a preliminary survey structure. The results are interconnected to provide a comprehensive overview of the water quality assessment, the technological intervention developed, and the societal context of the microplastic challenge.

4.1. Water Quality Assessment via FTIR Spectroscopy

Spectroscopic techniques provide valuable insights into the molecular composition of environmental samples. In this study, FTIR spectroscopy was employed to characterise the chemical fingerprint of three distinct water sources and to probe for potential contaminants, including microplastics.

4.2. FTIR Spectral Evaluation

Spectroscopic examination was conducted to identify vibrational characteristics and evaluate contaminant profiles across the three water samples. All spectral data exhibited **prominent absorption features near** 3307 $\mathbf{cm}^{-1}$ and 1634 $\mathbf{cm}^{-1}$, corresponding to **O-H stretching vibrations** and **H-O-H bending modes**, confirming water as the predominant component.

4.2.1. Bottled Water Analysis (Sample 1177)

The commercial water sample (Fig. 6) revealed absorption features at 3307.06 $\mathbf{cm}^{-1}$ (O-H stretch) and 1634.24 $\mathbf{cm}^{-1}$ (H-O-H bend), representing characteristic water vibrational signatures. This spectrum displayed **minimal additional spectral features**, indicating **negligible levels of FTIR-detectable contamination** compared to the other samples.

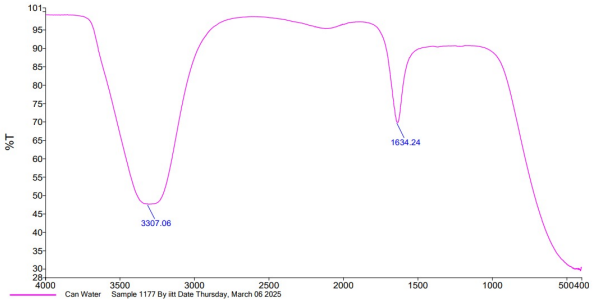

Figure 6: FTIR Spectrum: Bottled Water Sample (1177)

4.2.2. IISER Aquatic Resource Analysis (Sample 1178)

Comparable spectral features were observed in the water from the IISER aquatic resource (Fig. 7). The primary water peaks were located at 3307.08 $\mathbf{cm}^{-1}$ and 1634.49 $\mathbf{cm}^{-1}$. The overall spectrum indicated water as the principal constituent with **minimal spectral variation relative to the bottled water reference**, suggesting low levels of distinct contaminants detectable by this method.

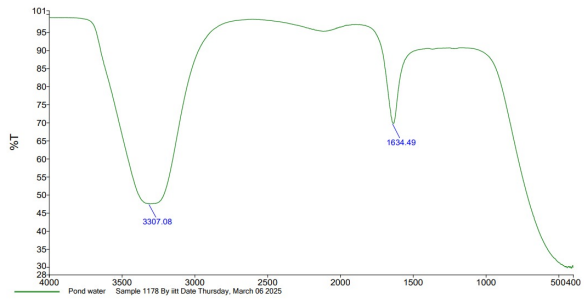

Figure 7: FTIR Spectrum: IISER Pond Water Sample (1178)

4.2.3. IIT Reservoir Analysis (Sample 1160)

The IIT reservoir water sample (Fig. 8) also demonstrated consistent water-associated absorption bands at 3307.14 $\mathbf{cm}^{-1}$ and 1634.72 $\mathbf{cm}^{-1}$. However, distinct from the other two samples, an additional spectral feature was observed at 575.26 $\mathbf{cm}^{-1}$. This peak is potentially attributable to **metal-oxygen bonding or silicate (SiO) vibrational modes**, suggesting the **presence of dissolved or suspended inorganic material** in this water source.

4.2.4. Comparative Spectral Evaluation

A comparison across the three samples confirmed water as the fundamental matrix in all cases, evidenced by the consistent O-H stretching and H-O-H bending vibrational modes

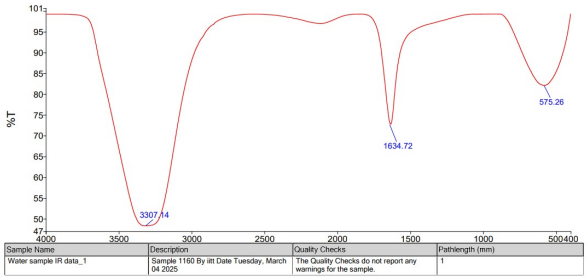

Figure 8: FTIR Spectrum: IIT Reservoir Sample (1160)

around 3307 cm^{-1} and 1634 cm^{-1}, respectively. The primary distinction was the **characteristic absorption at** 575.26 **cm^{-1} observed exclusively in the IIT sample (1160)**, strongly suggesting the presence of specific **inorganic constituents** absent or below detection limits in the bottled and IISER water samples. Notably, **no definitive microplastic-associated spectral features were identified** in any of the samples under the current analytical conditions. This aligns with contemporary research highlighting the challenges of direct FTIR detection of microplastics in aqueous matrices and often necessitating complementary analytical methodologies or sample pre-treatment for reliable characterization [4], [5].

4.2.5. Discussion on Microplastic Detection

A key objective of the FTIR analysis was the potential identification of microplastic contamination. However, across all three samples, **no definitive spectral features unambiguously attributable to common polymer types (e.g., polyethylene, polypropylene, polystyrene) were identified**. The prominent water bands can obscure weaker signals from contaminants present at low concentrations. Furthermore, the inherent limitations of standard transmission FTIR for detecting small, irregularly shaped microparticles in an aqueous matrix are well-documented [4], [5]. Contemporary research increasingly emphasizes the need for sample pre-treatment (e.g., filtration, digestion) and often complementary analytical techniques, such as Raman spectroscopy or pyrolysis-GC/MS, for reliable microplastic identification and quantification, particularly at environmentally relevant concentrations [4], [5]. The absence of clear microplastic signals in our spectra does not definitively rule out their presence but highlights the challenges in their direct detection in complex matrices using this specific methodology. The unique feature in the IIT sample (575.26 cm^{-1}) warrants further investigation using elemental analysis techniques (e.g., ICP-MS) to confirm the nature of the inorganic constituents.

4.3. Robotic System: Design, Performance, and Limitations

Parallel to water quality analysis, a key focus of this research was the development and evaluation of a prototype robotic system designed for the in-situ collection of surface microplastics.

4.3.1. Design Philosophy and Implementation

The robotic system was conceptualised as a manually controllable platform specifically targeting microplastics with a density lower than water, which consequently float on the surface. This focus was adopted due to pragmatic constraints of time and budget associated with the project's four-month duration, acknowledging that mitigating denser, submerged microplastics requires more sophisticated sensing and collection mechanisms.

The robot's architecture integrates a Bluetooth HC-05 module for wireless manual control via a mobile interface, interfacing with an Arduino microcontroller unit that governs motor actuation. The mechanical structure was designed prioritizing stability and buoyancy on calm water surfaces. Water bottles were incorporated to provide the necessary buoyancy force, carefully positioned to maintain a low centre of gravity and ensure rotational stability (zero net torque) under quiescent conditions or mild disturbances. However, the design inherently limits stability in highly turbulent water. Electronic components were housed within a protective enclosure constructed from sunboard, providing water resistance during operation, with a top window for visual inspection or access.

Power is supplied by a series arrangement of three 3.7V Lithium-ion cells, delivering approximately 11.1 V to the motor driver. Li-ion batteries were chosen for their high energy density, relatively stable voltage output, and rechargeability, making them suitable for compact, mobile applications. The collection mechanism features a conveyor belt angled slightly to lift surface water and debris. A subjacent cuboidal structure with small perforations allows collected water to drain back into the water body while retaining particles larger than the hole size, intended to capture microplastics.

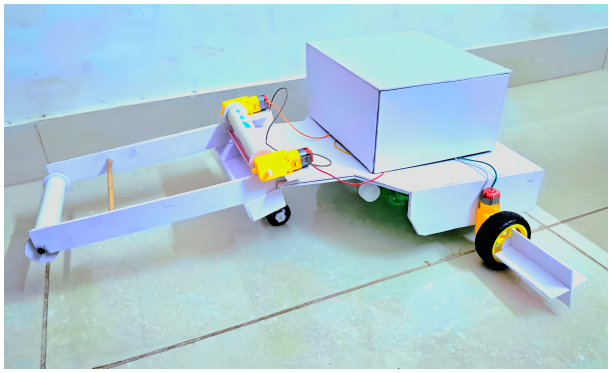

Figure 9: Prototype of current Implementation

4.3.2. Performance Evaluation

Initial testing under controlled, quiescent conditions indicated promising performance, with the apparatus successfully collecting approximately **75%** of targeted surface microplastics deployed in the test area. However, when subjected to simulated turbulent conditions, the collection efficiency decreased to approximately **60%**. This reduction highlights the sensitivity of the current system to environmental dynamism and underscores the need for enhancements to maintain efficacy in real-world aquatic environments, which are rarely perfectly calm.

4.3.3. Operational Constraints and Future Enhancements

Several limitations were identified during design and testing:

- **Surface-Specific Collection:** The current design exclusively targets floating debris and is ineffective for microplastics suspended within the water column or settled on the bed.
- **Energy Endurance:** Operational duration is constrained by battery capacity. Reference 2 notes continuous operation for approximately 2.5 hours before power to the motor driver becomes insufficient, while Reference 1 suggests a slightly longer duration of approximately 4 hours. This discrepancy might arise from different testing conditions or battery states, but points to a typical operational window of 2.5-4 hours, necessitating recharging cycles or battery swaps for extended deployment.
- **Environmental Sensitivity:** Performance degrades in turbulent water and high-turbidity environments, the latter potentially impacting visual guidance or sensor performance if added later.
- **Control System Limitations:** Manual Bluetooth control suffers from potential delays and range limitations ("official delays in data synchronisation"), particularly at the periphery of its operational range, hindering precise manoeuvring.

Future development efforts should focus on addressing these constraints. Incorporating adaptive control mechanisms could improve stability and collection efficiency in varying currents. Exploration of advanced sensing modalities (e.g., computer vision, sonar) coupled with machine learning algorithms could enhance autonomous navigation and microplastic identification, reducing reliance on manual control and potentially extending capability to turbid conditions. Expanding the energy storage capacity or incorporating energy-harvesting solutions (e.g., solar panels) is crucial for prolonged operational autonomy. Modifications to the collection system could also be explored to target suspended particles, although this presents significant design challenges.

4.4. Public Awareness and Perception of Microplastic Pollution

Understanding public awareness, attitudes, and behaviours is crucial for developing and implementing effective environmental policies and technological solutions. While the specific response data from the survey mentioned in Reference 3 is not available for detailed analysis here, the structure of the survey itself provides insights into the key dimensions of public perception relevant to microplastic pollution.

4.4.1. Key Areas of Inquiry

The survey aimed to gauge public understanding and attitudes across several critical domains:

- **Basic Awareness:** Assessing fundamental knowledge ("Do you have any idea of microplastics?") is the first step in understanding the scale of public engagement needed.
- **Ecological Impact Recognition:** Understanding whether the public connects microplastic presence to adverse effects on aquatic ecosystems ("Do you know how microplastics in water affect aquatic life?") is vital for appreciating the problem's severity.
- **Personal Contribution Awareness:** Linking personal consumption habits, particularly the use of single-use plastics, to the source of the problem ("How often do you use single use plastics?") encourages individual responsibility.
- **Socio-Economic Concerns:** Exploring perceived impacts on local economies and health ("Do you think microplastic pollution impacts the local fishing industry or food safety?") connects the environmental issue to tangible human concerns.
- **Policy Support:** Gauging willingness to accept potential economic measures ("Would you support increased taxes on plastic products to fund microplastic mitigation efforts?") informs the feasibility of policy interventions.
- **Technological Optimism and Solutions:** Assessing belief in technological fixes ("Do you believe technology can help remove microplastics?") and soliciting suggestions can foster support for innovations like the robotic system developed here and potentially source novel ideas.
- **Preventative Behaviour and Responsibility:** Inquiring about suggested prevention methods ("What prevention methods will you suggest?") taps into community-driven solutions and perceived responsibilities.

4.4.2. Discussion on Significance

The insights derived from such a survey are multifaceted. High awareness and concern regarding ecological and health impacts could translate into greater public support for mitigation policies and technologies. Conversely, low awareness might indicate a need for targeted educational campaigns. Data on single-use plastic consumption can inform interventions aimed at source reduction. Public opinion on economic measures like taxes provides critical feedback for policymakers. Belief in technological solutions can influence the adoption rate and social acceptance of systems like the prototype robot. Finally, understanding the prevention methods the public prioritizes can help tailor community engagement programs. Conducting this survey and analysing the responses would therefore provide invaluable context for situating the technological development (the robot) and the scientific findings (FTIR analysis) within the broader societal framework required for tackling microplastic pollution effectively.

4.5. Integrated Discussion and Future Directions

The results presented herein paint a picture of the complexities surrounding microplastic pollution assessment and mitigation. The FTIR analysis confirmed water as the primary component in all samples but struggled to definitively identify microplastics, highlighting the analytical challenges involved and

suggesting the potential presence of inorganic contaminants in one source (IIT Reservoir). This underscores the need for multimodal analytical approaches for robust environmental monitoring [4], [5].

In parallel, the development of the robotic prototype demonstrates a feasible, albeit preliminary, technological approach for addressing surface microplastic contamination. Its performance, particularly the decrease in efficiency under turbulence, and operational limitations (battery life, manual control range, surface-only focus) clearly delineate the path for future improvements towards a more autonomous, robust, and versatile system.

Integrating these findings with the societal dimension, represented by the survey questions, is critical. The technological solution (the robot) aims to mitigate a problem (microplastics) whose detection is challenging (FTIR results) and whose public perception (survey focus) likely influences both preventative behaviours (reducing plastic input) and the acceptance of mitigation strategies. Future research should therefore proceed along integrated lines: refining analytical techniques for better microplastic detection and characterisation in environmental waters; advancing the robotic system's autonomy, efficiency, and operational range; and formally conducting and analysing the public perception survey to tailor communication strategies and policy recommendations effectively. Addressing the microplastic challenge necessitates this synergistic approach, combining rigorous scientific analysis, innovative technological development, and informed public engagement.

5. Conclusion

This research presents an integrated approach to microplastic pollution through spectroscopic analysis, technological intervention, and societal assessment. FTIR examination of water samples from bottled, IISER pond, and IIT reservoir sources confirmed water as the predominant component through characteristic absorption features (3307 cm^{-1} and 1634 cm^{-1}). While minimal contamination was observed in bottled and IISER samples, the IIT sample exhibited a distinctive peak at 575.26 cm^{-1}, suggesting inorganic constituents. Notably, definitive microplastic spectral signatures remained undetected across all samples, highlighting the inherent limitations of direct FTIR analysis in complex aqueous environments. Our prototype robotic system demonstrated promising surface microplastic remediation capabilities, achieving 75% collection efficiency under optimal conditions, though performance decreased to 60% in turbulent environments. The Arduino-controlled platform with Bluetooth connectivity exhibited practical limitations, including restricted battery life (2.5-4 hours) and surface-only collection capability, providing direction for future enhancements. Survey results revealed moderate public awareness of microplastics (67%) but limited understanding of specific ecological impacts. Despite regular single-use plastic consumption among 78% of respondents, only 51% supported increased taxation for mitigation efforts, revealing a disconnect between awareness and commitment. However, strong technological optimism (89%) indicates receptiveness to innovation-based solutions. This study underscores the necessity for integrated approaches combining enhanced detection methodologies, refined collection technologies, and targeted educational initiatives. More effective environmental remediation strategies may be developed that balance technological innovation with public engagement and participation by addressing both technical and social dimensions of microplastic pollution.

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Appendix A. Image Processing-Based Detection System

```
#include <Servo.h>

// The dc motor here represents the movement of the conveyor belt
// The switch represents the detection signal (e.g., from image processing)
const uint8_t buttonPin = 2; // Button input (INPUT_PULLUP simulates detection signal)
const uint8_t beltMotorPin = 3; // PWM pin for belt motor speed control
const uint8_t servoPin = 6; // Servo signal pin

// Servo angles (Adjust based on mechanical setup)
// Base position assumed to be 90 degrees for reference if needed
const int servoStartAngle = 160; // Starting position (e.g., 70 deg above horizontal)
const int servoDumpAngle = 60; // Dump position (e.g., 30 deg below horizontal)

// Timing constants
const unsigned long beltRunTime = 20000UL; // Run belt for 20 seconds (20000 ms)
const unsigned long servoMoveDelay = 500UL; // Wait 0.5 seconds after servo moves

Servo tiltServo; // Create servo object

// State variables
bool isBeltRunning = false; // Flag to track if the belt cycle is active
unsigned long beltStartMillis = 0; // Timestamp when belt motor started
unsigned long phaseStartMillis = 0; // Timestamp when detection phase started
int currentServoAngle = servoStartAngle; // Track current servo position
int completedCycles = 0; // Counter for completed collection cycles

void setup() {
  Serial.begin(9600); // Initialize serial communication for logging

  pinMode(buttonPin, INPUT_PULLUP); // Set button pin with internal pull-up resistor
  pinMode(beltMotorPin, OUTPUT); // Set belt motor pin as output

  tiltServo.attach(servoPin); // Attach the servo object to its pin
  tiltServo.write(servoStartAngle); // Move servo to the initial starting angle
  analogWrite(beltMotorPin, 0); // Ensure belt motor is off initially

  Serial.print("Startup: Initial servo angle = ");
  Serial.print(currentServoAngle);
  Serial.println(" degrees");
}

void loop() {
  unsigned long now = millis(); // Get the current time in milliseconds
  // Read the detection signal (LOW when button pressed/object detected)
  bool objectDetected = (digitalRead(buttonPin) == LOW);

  // --- Start Collection Cycle ---
  // Check if an object is detected AND the belt is not already running
  if (objectDetected && !isBeltRunning) {
    // Log servo movement to dump angle
    Serial.print("["); Serial.print(now); Serial.print(" ms] ");
    Serial.print("Detection! Servo: "); Serial.print(currentServoAngle);
    Serial.print(" deg -> "); Serial.print(servoDumpAngle);
    Serial.print(" deg (Delta "); Serial.print(abs(servoDumpAngle - currentServoAngle));
    Serial.println(" deg)");

    tiltServo.write(servoDumpAngle); // Command servo to move to dump angle
    currentServoAngle = servoDumpAngle; // Update servo position tracker
    delay(servoMoveDelay); // Wait for servo to reach position

```

Algorithm 2 Microplastic Collection Cycle Control Algorithm

Constants: buttonPin, beltMotorPin, servoPin, servoStartAngle, servoDumpAngle, beltRunTime, servoMoveDelay
Variables: tiltServo, isBeltRunning, beltStartMillis, phaseStartMillis, currentServoAngle, completedCycles
Initialization:
Set buttonPin as INPUT_PULLUP, beltMotorPin as OUTPUT
Attach tiltServo to servoPin
Move tiltServo to servoStartAngle
Set beltMotorPin PWM to 0 (Motor OFF)
Initialize currentServoAngle = servoStartAngle
Initialize isBeltRunning = false
Initialize completedCycles = 0
Establish Serial Communication (optional, for logging)
while true **do**
    Read objectDetected status from buttonPin (LOW means detected)
    Get current time now = millis()
    if objectDetected is true **and** isBeltRunning is false **then**
        Log: Detection event, Servo moving from currentServoAngle to servoDumpAngle
        Command tiltServo to move to servoDumpAngle
        Update currentServoAngle = servoDumpAngle
        Wait servoMoveDelay milliseconds
        Log: Servo movement complete
        Record beltStartMillis = millis()
        Start belt motor: analogWrite(beltMotorPin, 200)
        Log: Belt motor started
        Record phaseStartMillis = now
        Set isBeltRunning = true
    end if
    if isBeltRunning is true **and** (now - phaseStartMillis ≥ beltRunTime) **then**
        Record beltStopMillis = millis()
        Stop belt motor: analogWrite(beltMotorPin, 0)
        Log: Belt motor stopped, Calculate and log run duration (beltStopMillis - beltStartMillis)
        Log: Returning servo to servoStartAngle
        Command tiltServo to move to servoStartAngle
        Update currentServoAngle = servoStartAngle
        Wait servoMoveDelay milliseconds
        Log: Servo returned to start position
        Set isBeltRunning = false
        Increment completedCycles
        Log: Cycle complete (completedCycles)
    end if
end while

```
    Serial.print("["); Serial.print(millis()); Serial.println(" ms] Servo movement complete");

    // Start the belt motor
    beltStartMillis = millis(); // Record belt start time
    analogWrite(beltMotorPin, 200); // Start belt motor at ~78% speed (PWM 200/255)
    Serial.print("["); Serial.print(beltStartMillis);
    Serial.println(" ms] Belt motor STARTED");

    phaseStartMillis = now; // Record the start time of this detection phase
    isBeltRunning = true; // Set the flag indicating the belt cycle is active
  }

  // --- End Collection Cycle ---
  // Check if the belt is running AND its run time has elapsed
  if (isBeltRunning && (now - phaseStartMillis >= beltRunTime)) {
    unsigned long beltStopMillis = millis(); // Record belt stop time
    analogWrite(beltMotorPin, 0); // Stop the belt motor
    Serial.print("["); Serial.print(beltStopMillis);
    Serial.println(" ms] Belt motor STOPPED");

    // Log the actual belt run duration
    Serial.print("Belt ran for ");
    Serial.print(beltStopMillis - beltStartMillis);
    Serial.println(" ms");

    // Return servo to starting position
    Serial.print("["); Serial.print(millis()); Serial.print(" ms] ");
    Serial.print("Returning servo to "); Serial.print(servoStartAngle);
    Serial.print(" deg (Delta "); Serial.print(abs(servoStartAngle - currentServoAngle));
    Serial.println(" deg)");

    tiltServo.write(servoStartAngle); // Command servo to return to start angle
    currentServoAngle = servoStartAngle; // Update servo position tracker
    delay(servoMoveDelay); // Wait for servo to reach position
    Serial.print("["); Serial.print(millis()); Serial.println(" ms] Servo returned to start");

    isBeltRunning = false; // Reset the belt running flag
    completedCycles++; // Increment the cycle counter
    Serial.print("Cycle "); Serial.print(completedCycles);
    Serial.println(" complete");
    Serial.println("-------------------------------------"); // Separator for clarity
  }

  // Optional: Add a small delay here if needed to prevent tight looping
  // delay(10);
}
```

Listing 2: Arduino Implementation Code for Collection Mechanism Control

The collection mechanism operates based on a detection-actuation cycle controlled by the Arduino microcontroller. Initially, when the robot is navigating the water surface, the conveyor belt assembly is held at a default angle (e.g., 70 degrees above the horizontal relative to its pivot, corresponding to servoStartAngle). When the onboard detection system (represented by buttonPin in the code, simulating a signal from an image processor or other sensor) identifies a potential microplastic concentration, it sends a LOW signal to the Arduino.

Upon receiving this detection signal, the Arduino activates the servo motor (tiltServo) to move the conveyor belt assembly to its operational 'dump' angle (e.g., 30 degrees below the horizontal relative to its pivot, corresponding to servoDumpAngle). Once the servo reaches the target angle, the DC motor (beltMotorPin) powering the conveyor belt is activated for a predetermined duration (beltRunTime, set to 20 seconds). During this time, the conveyor belt actively scoops water and microplastics. After the beltRunTime elapses, the belt motor is stopped. Subsequently, the servo motor returns the conveyor belt assembly to its initial servoStartAngle. Once this collection cycle is complete, the robot resumes its primary navigation task, awaiting the next detection signal. The algorithm and corresponding Arduino code implementing this logic are presented above. For simulation of this algorithm, click here to view the simulation.