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Eco Guardian: An IoT-Based Automated Plastic Waste Detection Solution for Mountain Ecosystem Conservation

Khuman Ravi K.[1], Mayur M. Jani[2]

[1]*PG Scholar, Department of CSE / IT, School of Engineering & Technology, Dr. Subhash University, Junagadh, Gujarat, India*

[2] *Assistant Professor, Department of CSE / IT, School of Engineering & Technology, Dr. Subhash University, Junagadh, Gujarat, India*

ABSTRACT

This Study presents a novel framework leveraging Internet of Things (IoT) technologies for environmental protection in mountainous regions. The proposed solution utilizes a smart, sensor-equipped detection system—integrating real-time imaging and machine learning models—to automatically identify, classify, and monitor plastic waste dispersed throughout sensitive mountain ecosystems. Data collected by connected monitoring stations are continuously transmitted for central analysis, enabling rapid response to pollution hotspots and guiding targeted clean-up operations. By providing automated waste mapping, instant alerts, and long-term environmental data, Eco Guardian enhances conservation decision-making and reduces the burden of manual surveillance, thus supporting both sustainability and biodiversity conservation in fragile high-altitude habitats.

Keywords: Plastic pollution, Plastic Waste Detection, Mountain Ecosystem Conservation, Automated Monitoring, Environmental Sustainability, Machine Learning, Smart Sensors, Real-Time Surveillance, Biodiversity Protection, Remote Sensing

I. INTRODUCTION

Mountains are among the world's most ecologically significant and sensitive regions.

Plastic pollution has emerged as a leading threat to fragile mountain environments worldwide. As tourism and local activities grow, so does the accumulation of unrecycled plastic, endangering wildlife, water sources, and the natural beauty of these unique regions.

However, the increasing spread of plastic waste threatens the biodiversity, ecosystem health, and aesthetic value of mountain environments. Traditional manual cleanup methods are inefficient and insufficient given the vastness and inaccessibility of mountain terrains.

Manual patrols and clean-up drives in mountain areas are often ineffective due to inaccessible terrain, large coverage area, and high labor costs. Also Manual detection is time-consuming, error-prone, and labour - intensive, especially in remote regions.

So recent breakthroughs in IoT, computer vision, and artificial intelligence & Machine learning have revolutionized environmental management by enabling automated, large-scale monitoring and precise detection of plastic waste.

These technologies empower real-time identification and rapid alert systems, transforming how authorities and communities respond to pollution challenges in even the most remote and challenging landscapes.

II. LITERATURE REVIEW

Sr.	Year / Author	Title	Research Objective	Methodology	Limitation (Research Gap)
1	2025 - Ansarullah Lawi [1]	Development of an IoT-Based Mobile Plastic Shredder for Optimized Waste Management in Batam	The objective of this research is to design and develop an IoT-based mobile plastic shredding machine that improves waste management efficiency in Batam, Indonesia, by enabling real-time monitoring, automated plastic processing, and portability for optimized and sustainable plastic waste reduction.	This research uses the **Borg and Gall's Research and Development (R&D) Framework** methodology. It involves systematic stages like research, planning, prototyping, field trials, and continuous revisions to develop the **IoT-based plastic shredder.**	The main limitation of this paper is that the evaluation and application of the IoT-based plastic shredding machine are restricted to a specific location **(Batam),** with limited long-term data and scalability testing in diverse environments.
2	2025 – Cosmina-Mihaela Rosca [2]	Innovative AIoT Solutions for PET Waste Collection in the Circular Economy Towards a Sustainable Future	The purpose of this research is to develop a **low-cost AIoT-based PET Recycling System (PRS)** that can accurately identify and accept crushed or deformed PET bottles using the **PET Bottle Identification Algorithm (PBIA)** and Azure Custom Vision.	The methodology used in this research combines **AIoT-based hardware (Asus Tinker Board with sensors, cameras, and load cell)** for PET bottle collection and sorting with **software algorithms (PBIA and ACTLR)** integrated with Azure Custom Vision for object	A key limitation of this paper is that the **PET Bottle Identification system heavily depends on cloud connectivity (Azure Custom Vision),** making it vulnerable in areas with poor or unstable internet.
3	2025 – Marco Balsi [3]	Plastic Litter Detection in the Environment Using Hyperspectrl Aerial Remote	The objective of this research is to **develop and validate a drone-based hyperspectral remote sensing system (SWIR band) with**	This paper uses a **drone-mounted hyperspectral sensor (SWIR band: 900–1700 nm)** to capture	A key limitation of this paper is that the approach was tested mainly on **drone-based hyperspectral data in controlled or small-**

Sr.	Year / Author	Title	Research Objective	Methodology	Limitation (Research Gap)
		Sensing and Machine Learning	**machine learning** for accurate detection of plastic litter in diverse environments.	spectral data of plastics in different environments. The data are processed using **machine learning methods (LDA, SVM with feature selection via mRMR)** for real-time plastic litter detection.	**area environments, not yet on large-scale or highly scattered litter** scenarios.
4	2024 – Priyanka Madhiraju [4]	IoT-Driven Defect Detection System for Plastic Recycling Plants based on Convolutionl Neural Networks	The purpose of this study is to develop an IoT-driven defect detection system using **Convolutional Neural Networks (CNNs)** to enhance accuracy, efficiency, and real-time monitoring in plastic recycling plants. **The system aims to minimize human errors, improve quality control, and support sustainable recycling operations by automating flaw detection such as contamination, discoloration, and physical damage**	The main methodology used in this paper is **integration of IoT sensors for real-time data acquisition and Convolutional Neural Networks (CNNs)** for defect detection and classification in plastic materials	The main research gap of this paper is the **need for scalability and integration with existing recycling infrastructure**, along with **challenges in deploying the system under diverse real-world operating conditions.**
5	2024 – Uriel Martinez-Hernandez[5]	Low-Cost Recognition of Plastic Waste Using Deep Learning and a Multi-Spectral Near-Infrared Sensor	The main research objective of this paper is to **develop a low-cost approach for recognizing different types of household plastic waste using a multi-spectral near-infrared sensor combined with machine learning**	The main methodology used in this paper is the **integration of a low-cost multi-spectral near-infrared (NIR) sensor** for data collection and application of **machine learning**	The main limitation of this paper is that the **recognition accuracy (max ~72.5%) is lower than expensive spectroscopy systems**, and the **dataset size and plastic variety are limited, affecting robustness for large-**

Sr.	Year / Author	Title	Research Objective	Methodology	Limitation (Research Gap)
			methods, thereby enabling affordable, portable, and sustainable solutions for recycling and circular economy applications	**models (e.g., CNN, MLP, SVM)** with dimensionality reduction (PCA/LDA) for plastic waste recognition	**scale real-world recycling applications**.
6	2024 – Namratha [6]	IoT Based Plastic Wate Management System For Smart City Applications.	The main objective of this paper is to introduce an **innovative IoT solution for smart cities** that transforms waste management. This is achieved by integrating a **Node MCU, various sensors, and the Blynk application** to address challenges in waste segregation, material identification, and real-time monitoring	**IoT-based plastic waste management system**. It involves integrating components like the **Node MCU, capacitive sensors, inductive sensors, a weight sensor, and the Blynk application** to handle waste segregation and real-time monitoring.	based on the literature survey, a potential limitation is that while it focuses on an **IoT solution for plastic waste**, other studies have integrated more advanced technologies like **deep learning** and **machine learning** for improved classification accuracy and efficiency.
7	2024 – Cesar Lubongo [7]	Recent Developments in Technology for Sorting Plastic for Recycling: The Emergence of Artificial Intelligence and the Rise of the Robots	The main objective is to review the application of machine learning models to address the issue of plastic waste management. The research aims to determine the efficiency and effectiveness of these methods for plastic waste detection and classification.	The paper "Recent Developments in Technology for Sorting Plastic for Recycling" discusses various methods for plastic identification, including spectroscopy augmented by **machine learning algorithms such as supervised, unsupervised, semi-supervised, and reinforced learning.**	Based on the paper, a key limitation is the **challenge of sorting films, dark plastics, and multi-polymer plastics**. Another gap is that while optical sorters have high efficiency, they are primarily designed **for rigid plastics and are less effective for 2D materials like films.**
8	2024 – Owen Tamin[8]	On-Shore Plastic Waste	The research objective of this paper is to	Query successful The paper's	he paper's limitations include focusing only on

Sr.	Year / Author	Title	Research Objective	Methodology	Limitation (Research Gap)
		Detection with YOLOv5 and RGB-Near-Infrared Fusion: A State-of-the-Art Solution for Accurate and Efficient Environmental Monitoring	**develop a plastic waste detection system using a YOLOv5-based model** and to **compare the effectiveness of using RGB (visible light) and RGNIR (near-infrared) images** for this purpose. The study aims to determine if the fusion of both RGB and RGNIR datasets can improve the overall performance of the detection system.	limitations are that it primarily focused on the YOLOv5m architecture and did not explore other model sizes.	the YOLOv5m architecture, neglecting other model sizes. Future research is needed to test the model's robustness at different camera distances and with varying image resolutions.

III. RESEARCH GAP AND OBJECTIVES

3.1 Identified Research Gaps

- No wide-scale, ruggedized sensor systems tailored specifically for **mountain plastic waste detection.**
- Difficulties in real-time data integration and energy efficiency in remote areas.
- Gaps in community notification mechanisms for immediate remedial action.
- Limited datasets for training accurate plastic detection models in natural, unstructured environments.
- **Environmental Adaptability:** Difficulty in handling diverse mountain weather and terrain variations.
- **Energy Constraints:** Insufficient solutions for power supply to distributed sensors in off-grid mountaintop locations.

3.2 Research Objective

- Develop and deploy an IoT-based solution for real-time plastic waste detection in mountain regions & Also Design a low-power, weatherproof IoT sensor network for automated plastic waste detection in mountainous ecosystems.
- Design robust, energy-efficient sensor nodes to operate in harsh, variable climatic conditions.
- Integrate AI/ML models for automatic visual detection and reliable waste identification and location mapping.
- Establish a central monitoring and alert system, enabling rapid reporting and response.
- Validate the solution through field trials in representative mountain segments.

3.3 Problem Definition

- Manual attempts to monitor and control plastic waste in mountain ecosystems are inadequate due to accessibility, size, and resource constraints.
- Also a Plastic debris accumulation is accelerating in mountain regions due to limitations in surveillance, resource constraints, and inadequate public awareness.
- This research aims There is a need for an automated, low-power, scalable, and adaptive system capable of accurately identifying, classifying, and reporting plastic waste deposits—even in challenging terrain and weather conditions—to support effective conservation.

3.4 Probable Outcomes

By the end of this research, anticipate the following outcomes:

- Higher detection accuracy and faster clean-up response compared to traditional methods.
- Real-time, geo-tagged plastic litter database for targeted cleaning strategies.
- Increased participation of local communities and tourists in plastic monitoring and cleanup. Also Increased public awareness and engagement using real-time data dashboards.

IV. METHODOLOGY

- This research will involve a combination of IOT, Machine Learning , image processing and deep learning for plastic waste detection and classification.
- Sensor Design: Deploy compact, solar-powered IoT devices equipped with cameras and environmental sensors. Plan eco-friendly, sensor-based IoT nodes (using cameras, environmental sensors)
- Machine Learning: Train and integrate algorithms (e.g., YOLOv5(“ You Only Look Once ”) , CNNs) to distinguish plastic waste from natural surroundings.
- Network Deployment: Install sensor nodes in key locations, connected via wireless mesh or LoRaWAN networks.

V. FUTURE SCOPE AND ENHANCEMENTS

- In this phase the main aim of the proposed work has been accomplished. The findings and conclusion of the recently conducted study has been given in previous section. In this section, the future plan of the proposed study has been given as:
- Scale deployment to different geographic regions and ecosystems.
- Enhance sensor hardware for additional waste types (e.g., glass, metal).
- Improve power systems by adding renewable energy harvesting.
- Integrate public participation features (e.g., reporting via mobile apps).
- Collaborate with policymakers for broader ecological action.

VI. CONCLUSION

Eco Guardian aims to shift plastic waste management in mountain regions from fragmented, manual effort to systematic, technology-driven action.

By harnessing IoT and AI-ML, it promotes faster detection, accurate response, and enhances the sustainability of sensitive mountain environments.

Also concludes that integrating IoT technologies with machine learning for plastic waste detection significantly enhances conservation and waste management efforts in sensitive mountain environments

This system enables real-time monitoring, automated identification, and efficient mapping of plastic waste, greatly reducing manual intervention and enabling proactive, data-driven clean-up strategies.

By providing instant alerts and historical data analytics, the solution fosters swift responses to environmental threats and supports better long-term planning.

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