



From Waste to Worth: AI and IoT-Based System for Predictive Waste Management and Eco-Product Innovation

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I. Abstract –

As urban populations grow and consumption rates rise, conventional waste management systems face mounting inefficiencies, leading to environmental harm and lost opportunities for resource recovery. To address these challenges, this paper presents ReArtify (a web based application), a tech-driven platform that integrates Artificial Intelligence (AI), Machine Learning (ML), and Internet of Things (IoT) to enable smart, sustainable waste management [10].

ReArtify employs AI-powered image classification to accurately identify and segregate waste types, while offering creative upcycling suggestions based on material composition. A built-in recommendation engine supports eco-artists and sustainable businesses with insights into material availability and market trends. IoT-enabled smart bins equipped with image and weight sensors gather real-time data, enabling predictive analysis of area-wise waste generation to optimize collection schedules.

The platform also features a centralized web marketplace that connects waste generators with environmentally conscious creators, promoting circular economy principles. Interactive dashboards provide users and policymakers with metrics such as CO₂ savings, recycling rates, and sustainability scores. Additionally, ReArtify fosters behavioral change through gamification and incentives, and explores future enhancements like blockchain-based waste traceability and ESG-integrated reporting.

ReArtify exemplifies a scalable, holistic approach to transforming urban sustainability through intelligent, data-driven innovation.

Keywords: Waste Management, Smart Bins, Upcycling, Circular Economy, Eco-Art. [10]

II. INTRODUCTION

The exponential rise in global population, rapid urbanization, and increasing consumerism have led to a mounting crisis in waste management. According to the World Bank's "What a Waste 2.0" report, global municipal solid waste generation is projected to reach 3.4 billion tonnes annually by 2050, up from 2.01 billion tonnes in 2016. Most of this waste—particularly plastic, e-waste, and hazardous materials—is either dumped into landfills or incinerated, contributing significantly to environmental pollution, greenhouse gas emissions, and public health hazards.

Traditional waste management practices rely heavily on manual labor, centralized collection systems, and outdated infrastructure. These approaches often result in improper segregation, inefficient resource recovery, and excessive operational costs. Furthermore, a substantial volume of recyclable and reusable materials is lost in the absence of smart sorting mechanisms and end-user engagement. The disconnect between waste generators, recyclers, and creative industries further exacerbates the problem, hindering the realization of a truly circular economy.[7]

Simultaneously, the growing interest in sustainability, upcycling, and environmentally-conscious practices among individuals and communities has created a unique opportunity to transform waste into a resource. Small-scale artisans, eco-startups, and artists frequently seek unconventional raw materials for creative production but lack access to organized, categorized waste sources. Thus, there is a critical need for a technology-driven solution that facilitates intelligent waste segregation, enhances visibility across the waste value chain, and connects stakeholders in a meaningful way.

ReArtify is conceived as a holistic response to these challenges. It is an AI and IoT-enabled digital platform that leverages cutting-edge technologies to bring innovation into the waste management ecosystem. Through machine learning models trained on waste image datasets, ReArtify automates classification of waste into various categories such as plastic, paper, organic, metal, and e-waste. The system further enhances utility by recommending eco-product ideas and forecasting material demand based on historical trends and regional insights.

IoT-based smart bins integrated with image and weight sensors offer real-time monitoring and data collection. These smart devices predict the volume and composition of waste at the source, enabling efficient planning for waste pickup and recycling operations. Additionally, ReArtify features a user-friendly analytics dashboard and a digital marketplace that brings together waste producers and eco-artists to encourage upcycling and sustainable product creation. [10]

By addressing existing gaps in waste management through digital innovation, ReArtify aspires to contribute meaningfully to global sustainability goals and foster responsible consumption and production behaviors.

III. METHODOLOGY

The development of ReArtify follows a modular and data-driven approach that integrates AI-based waste classification, ML-driven recommendations, IoT-enabled smart bins, and a web-based platform to facilitate

upcycling and sustainability. [10]

1. AI-Powered Waste Classification

- i. **Dataset Preparation:** Images were sourced from publicly available datasets like TrashNet and TACO, as well as through field photography. Images were labeled into categories such as plastic, metal, glass, organic, and e-waste.[3]
- ii. **Preprocessing:** Data augmentation (rotation, flipping, noise addition), normalization, and resizing were performed to improve generalization and model robustness.
- iii. **Model Architecture:** Various ML models were evaluated, with Convolutional Neural Networks (CNNs) providing the best results in accuracy and precision. TensorFlow and Keras libraries were used for development.[6],[4]
- iv. **Model Training & Testing:** The dataset was split into training, validation, and testing sets. Metrics such as accuracy, precision, recall, and F1-score were tracked.
- v. **Deployment:** The trained model was deployed as a Flask API integrated with the frontend, providing real-time classification of uploaded waste images.

2. ML-Based Recommendation System

- i. **User Data Collection:** Browsing behavior, user preferences, and location data were collected and anonymized.
- ii. **Recommendation Algorithm:** A hybrid system was implemented, combining collaborative filtering and content-based filtering to recommend upcycling ideas and eco-products.
- iii. **Trend Forecasting:** Historical usage patterns and seasonal data were used to forecast material demand in specific locations using time-series models.[1]
- iv. **Personalization Engine:** TensorFlow Recommenders was used to implement custom suggestions for artists and users.

3. IoT Smart Bin Design

- i. **Hardware Components:** Each bin was equipped with load cells (to measure weight), camera modules (for image capture), a microcontroller (Raspberry Pi or Arduino), and a communication module (GSM/Wi-Fi).[7],[10]
- ii. **Firmware Programming:** Arduino IDE and Python scripts were used to manage sensor readings, data logging, and conditional alerts (e.g., overflow detection).
- iii. **Data Transmission:** Data from sensors was sent to a cloud database using MQTT and HTTP protocols. In low-connectivity areas, local storage and batch uploading were utilized.[10]
- iv. **Smart Features:** Bins included indicators (LEDs) for fullness, solar panels for off-grid use, and modular compartments for different waste types.

4. Web Platform & Digital Marketplace

- i. **Frontend:** Developed using React.js, HTML5, Tailwind CSS, and Chart.js for responsive design and real-time data visualization.
- ii. **Backend:** Built on Node.js and Express.js, handling API routing and database operations. MongoDB was

chosen for its flexibility and scalability in handling user data, product listings, and IoT logs.

- iii. **Marketplace Functionality:** Artists can list products, request specific waste types, and communicate with waste contributors via integrated chat and notifications.

5. Analytics Dashboard

- i. **Data Aggregation:** Data from AI models, IoT bins, and user activity is collected in a central MongoDB instance and periodically cleaned and structured.
- ii. **Visualization:** Google Maps API was used to render geospatial waste trends; Chart.js was used for comparative and trend graphs.
- iii. **KPIs:** Metrics such as total waste collected, segregation efficiency, CO₂ emissions saved, and product upcycle counts are displayed in real time.[9]

6. Security and Hosting Infrastructure

- i. **User Authentication:** Firebase Authentication was used to ensure secure and role-based access control.
- ii. **Cloud Hosting:** The app was hosted on Firebase and AWS EC2 instances. MongoDB Atlas hosted the database in a cloud environment.
- iii. **Data Security:** HTTPS protocol, hashed credentials, two-factor authentication, and periodic backups ensured platform security and resilience.

7. Process Flow: Interaction Between Users, Collectors, and Artisans

- i. **Users (Waste Generators):** Regular users interact with the system by uploading images of their waste, receiving classification and segregation guidance, and viewing their environmental impact metrics through the analytics dashboard. They can also earn eco-points for regular segregation and contribute materials to the marketplace.
- ii. **Collectors:** Municipal or private waste collectors access real-time data from IoT bins through the dashboard, enabling them to optimize pickup routes and prioritize full bins. They also receive alerts on material demand and user requests for pickup scheduling.
- iii. **Artisans (Eco-Product Creators):** Artists and small-scale businesses browse the digital marketplace for available segregated waste suitable for upcycling. They can place requests for specific materials, upload their own eco-product listings, and engage with the community through product reviews and sustainability stories.

This interconnected workflow fosters a circular economy where waste becomes a shared resource, encouraging transparency, community participation, and sustainability at each stage.

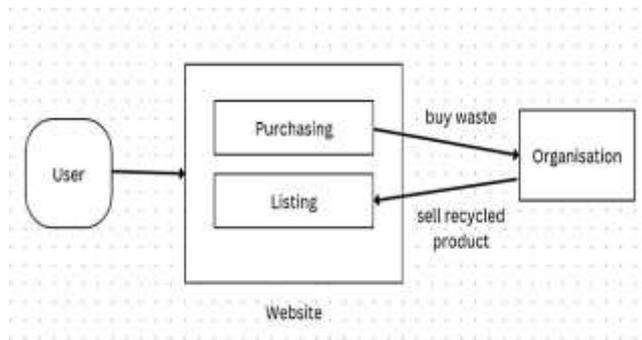


Fig. 1 (User).

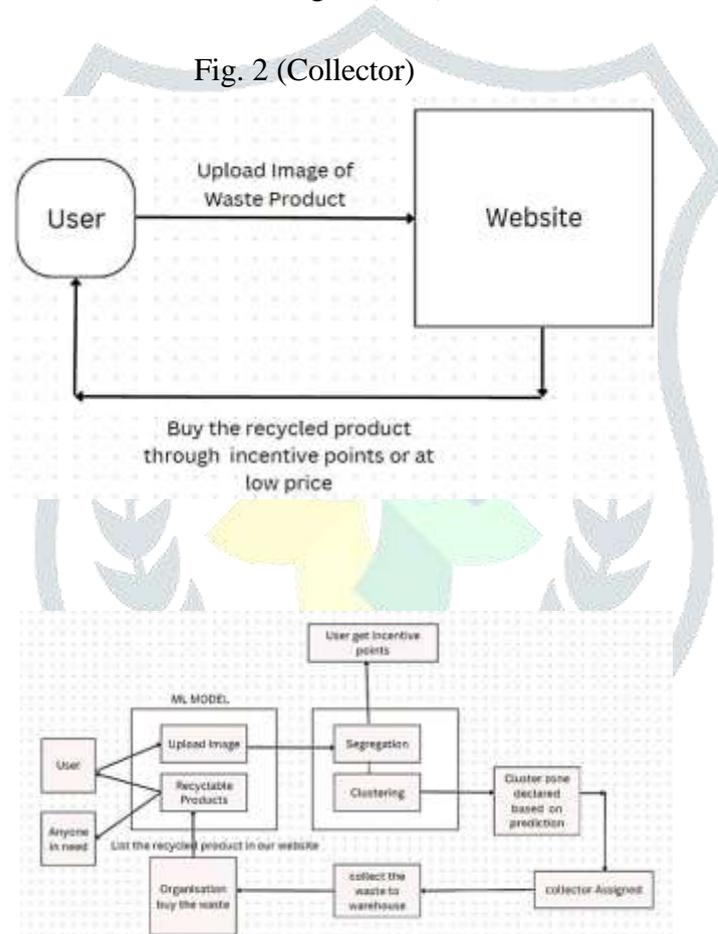


Fig. 3 (Segregation Model)

IV. CHALLENGES

Despite the promising potential of ReArtify, the development and deployment phases presented numerous technical, logistical, and societal challenges. Identifying and addressing these challenges was crucial to the platform's refinement and functionality.

1. Data Scarcity for Waste Classification

- i. Publicly available waste datasets are limited in size, diversity, and quality. Most existing datasets lack real-world complexity such as mixed waste, varied lighting, and irregular backgrounds.[4],[5],[8]
- ii. **Mitigation:** Synthetic data generation techniques and data augmentation were employed to expand training data. Field-collected images enhanced diversity.

2. Model Performance on Mixed Waste

- i. Classification models showed reduced accuracy when encountering images with multiple overlapping waste types.
- ii. Mitigation: Fine-tuning CNN architectures and exploring multi-label classification techniques helped improve robustness.

3. Sensor and Hardware Limitations in IoT Bins

- i. Sensors are prone to drift and noise, and may fail under extreme environmental conditions such as heat, moisture, or dust.[7],[10]
- ii. Mitigation: Calibration protocols and environmental enclosures were introduced. Sensor fusion approaches are under consideration.

4. Connectivity and Power Issues in Remote Areas

- i. Inconsistent internet access and power supply hindered real-time data transmission.
- ii. Mitigation: Local data caching and solar-powered units were implemented to maintain functionality in low-infrastructure regions.

5. Behavioral Resistance from End Users

- i. Many users were unfamiliar with waste segregation practices or reluctant to change existing disposal habits.
- ii. Mitigation: Educational campaigns, incentives, and gamified features (e.g., eco-points) were designed to encourage participation.

6. Data Privacy and Ethical Considerations

- i. Collecting user data for recommendations and analytics posed challenges in maintaining transparency and compliance.
- ii. Mitigation: Adherence to GDPR guidelines, anonymized data handling, and opt-in policies ensured ethical data usage.

7. Integration Across Heterogeneous Technologies

- i. Ensuring smooth communication between AI models, IoT devices, cloud services, and user interfaces was complex.
- ii. Mitigation: RESTful APIs and asynchronous communication protocols were used to manage data flow effectively.

8. Scaling Infrastructure with Growing Demand

- i. As the number of users and bins increases, maintaining performance, uptime, and affordability becomes challenging.
 - ii. Mitigation: Cloud auto-scaling and microservices architecture were explored to support horizontal scaling.
- These challenges underline the complexity of building an end-to-end smart waste management system, and the adaptive strategies used in ReArtify's development can serve as valuable insights for future projects in the sustainability tech domain

V. DISCUSSION

The ReArtify project demonstrates the powerful convergence of AI, IoT, and sustainability in addressing one of the most persistent urban challenges: inefficient waste management. Through the implementation of machine learning models for waste classification and IoT-based smart bins for area-wise waste prediction, the system effectively bridges the gap between waste producers, recyclers, artists, and eco-conscious consumers. [10]

Initial experiments with the AI waste classification model yielded promising accuracy levels, particularly in identifying recyclable materials such as plastic, metal, and paper. However, real-world testing highlighted the complexity of dealing with mixed or contaminated waste, reinforcing the need for continuous model refinement using larger and more diverse datasets. The model's recommendation system also successfully identified trends in eco-products, aiding artists in choosing market-relevant upcycling ideas. The smart bin prototype, equipped with load and image sensors, provided granular data on waste generation patterns across different areas. [10]

This data, when visualized through the analytics dashboard, revealed actionable insights for waste collectors and municipal bodies—enabling more efficient waste routing and resource deployment. Additionally, the CO₂ savings metric allowed users and policymakers to understand the tangible environmental benefits of upcycling and proper segregation. [9]

The marketplace component of ReArtify added a unique social and economic layer, empowering local artisans by connecting them with raw materials and an online audience. This not only promoted sustainable livelihoods but also encouraged community participation in environmental practices.

Despite its success, the project revealed several challenges—particularly around data availability, real-world sensor calibration, and behavior change among users. However, these challenges also offered opportunities for innovation, such as using synthetic data for model training, integrating mobile alerts for bin overflow, and gamifying user participation through eco-points or reward systems.

In a broader context, ReArtify aligns with global sustainability goals (SDGs), especially SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). [9] Its potential scalability, integration with blockchain for waste traceability, and compatibility with CSR and NGO initiatives make it a strong candidate for real-world deployment.

VI. RESULT

Aspect	Existing Solution	Our Solution
Waste Collection	Inefficient, mixes recyclable & non-recyclable waste.	Directs waste to artists for repurposing.
Waste Segregation	Costly & manual..	Encourages smart segregation at the source.
Waste Utilization	Mostly dumped or incinerated.	Converts waste into valuable products.
Support for Artists	No dedicated platform for artisans.	Provides materials & a marketplace for eco-products.
Economic Impact	Minimal employment opportunities.	Creates jobs & supports sustainable businesses.
Technology Use	No data-driven insights.	AI-powered tracking of waste, CO ₂ savings & trends.
Personalization	No tailored user experience.	ML-based suggestions for users & artists.

VII. CONCLUSION

ReArtify stands at the intersection of innovation, sustainability, and technology, providing a comprehensive and scalable solution to the pressing challenges of waste management. By leveraging the capabilities of Artificial Intelligence, Machine Learning, and IoT, the platform not only automates waste classification but also enhances efficiency, traceability, and transparency across the waste management lifecycle.

The AI-powered classification module brings precision to the segregation process, ensuring that recyclable and upcyclable materials are identified correctly. The IoT-enabled smart bins provide real-time data on waste generation patterns, empowering municipal bodies and collectors to plan operations proactively and

efficiently. The integrated recommendation engine personalizes experiences for users and artists alike, bridging the gap between waste generators and upcyclers. [10]

ReArtify's user-centric approach is further strengthened by its real-time analytics dashboard and digital marketplace, which democratizes access to raw materials and eco-products. This unique blend of functionality promotes circular economy practices while fostering community engagement and behavioral transformation through gamified rewards and environmental impact visualizations.

Despite the challenges related to data, hardware limitations, user behavior, and technology integration, ReArtify's adaptive methodology and modular design have demonstrated resilience and scalability. The platform holds immense potential for deployment in both urban and rural settings, aligning closely with global sustainability goals such as SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

VIII. FUTURE SCOPE

The ReArtify platform opens several promising avenues for future development, both technologically and socially:

1. **Blockchain Integration for Waste Traceability**

Introducing blockchain technology to ensure transparent tracking of waste from collection to upcycling. This could enable a system of verifiable waste credits and boost trust among users, artists, and policymakers.

2. **Gamification and User Incentivization**

Adding eco-point systems, badges, and reward-based features to promote consistent user participation in waste segregation and recycling efforts.

3. **Integration with Government and CSR Initiatives**

Collaborating with municipal bodies, CSR programs, and NGOs to deploy ReArtify at scale across smart cities and under sustainable urban planning missions.

4. **Real-Time Route Optimization for Waste Collection**

Using AI to optimize waste collection routes based on real-time IoT bin data to save fuel, reduce emissions, and minimize collection costs.

5. **Advanced Image Recognition with Deep Learning [4]**

Upgrading the waste classification model using deep learning (e.g., Convolutional Neural Networks) to improve accuracy on mixed or degraded **waste** images. [4]

6. **Mobile Application and Offline Capabilities**

Launching a lightweight Android/iOS app with offline support to expand reach in low-connectivity rural and semi-urban areas.

7. **Sustainability Reports and ESG Integration**

Enabling downloadable sustainability reports for companies using the platform, helping them meet Environmental, Social, and Governance (ESG) reporting requirements.

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