Automated Detection of Recyclable Waste in Real-Time Using Deep Learning and Computer Vision Techniques

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Abstract: **The growing volume of unmanaged solid waste poses significant environmental and operational challenges in urban settings. Traditional scrap segregation is labour-intensive, error-prone, and lacks consistency, especially in regions where manual sorting dominates the recycling process. This research presents a real-time recyclable and non-recyclable material detection system powered by YOLOv5 and Convolutional Neural Networks (CNN), integrated with OpenCV for live camera-based waste identification. A custom-labelled dataset was developed, comprising diverse waste categories such as plastic, iron, cardboard, books, motors, and non-recyclable items to address real-world scrap scenarios. The YOLOv5 model was trained and optimized on this dataset, achieving high accuracy and rapid inference speeds suitable for deployment in industrial or public recycling environments. The system processes live video feeds and detects multiple objects simultaneously with bounding boxes and class labels, demonstrating robust performance under varying lighting and background conditions. The proposed solution significantly reduces manual effort, supports real-time sorting, and provides a scalable approach for smart waste management. This research aims to bridge the gap between intelligent computer vision applications and sustainable waste handling by enabling reliable, fast, and cost-effective classification of scrap materials.**

Keywords: Deep Learning, YOLOv5, Computer Vision, Waste Classification, Recyclable Materials, OpenCV.

I. INTRODUCTION

The rapid rise in global waste generation has placed immense pressure on conventional waste management systems, especially in urban environments. Manual segregation of waste materials, a common practice in many developing regions — is not only inefficient and labour-intensive but also exposes workers to health risks and often leads to misclassification of recyclable materials. With the growing emphasis on sustainability and automation, there is a critical need for intelligent systems that can identify, classify, and sort waste in real time to improve recycling efficiency and reduce human dependency.

Recent advancements in computer vision and deep learning, particularly object detection algorithms like YOLO (You Only Look Once), have made it possible to automate visual classification tasks with high accuracy and speed. This research proposes a real-time recyclable waste detection system based on the YOLOv5 architecture integrated with OpenCV for live video processing. A custom-labeled dataset was developed consisting of real-world recyclable and non-recyclable material classes, such as plastic, iron, cardboard, motors, books, and other common waste types found in scrap yards. The proposed system can identify and classify multiple objects simultaneously from a live camera feed, providing a scalable and accurate solution for industrial and urban waste management operations.

By replacing manual sorting with AI-powered automation, this work contributes to the growing field of smart waste management and presents a practical framework that can be deployed in real-world scrap collection and recycling environments. The system's performance demonstrates the potential of combining deep learning with real-time vision tools to achieve efficient and intelligent waste handling.

II. LITERATURE SURVEY

In recent years, computer vision and deep learning have shown great success in solving real-world problems, including waste classification and recycling automation. Many researchers have worked on systems that can detect and categorize waste items using neural networks and image processing. These systems help reduce manual effort, improve recycling accuracy, and promote environmental awareness.

A paper by Andhy Saputra et al. proposed a method using YOLOv4 and YOLOv4-tiny for classifying four types of waste: plastic, metal, paper, and glass. Their dataset included over 3,000 images, and the model was tested on images, videos, and webcam feeds. The results showed that YOLOv4 achieved better accuracy, while YOLOv4-tiny was faster and suitable for low-resource systems. Another study by Chinnathurai et al. used Content-

Based Image Retrieval (CBIR) techniques to detect waste items but faced limitations in terms of accuracy and response time.

Some researchers explored traditional machine learning approaches such as K-Nearest Neighbors (KNN), Support Vector Machines (SVM), and Decision Trees for waste classification. However, these methods often require handcrafted features and struggle with real-time video data. To overcome such limitations, modern object detection models like YOLO (You Only Look Once) and SSD (Single Shot MultiBox Detector) are now widely preferred due to their ability to process live images with high accuracy and speed.

In addition to these, various studies have integrated smart IoT systems for monitoring waste bins and automating sorting processes. However, such systems are usually expensive or complex to deploy in small scrap centers or local environments. Some research also explored integrating AI with robotics for automated sorting arms, but again, cost and scalability remain concerns.

After reviewing multiple research works related to waste classification, object detection, and deep learning, we observed that YOLO-based models are currently the most practical choice for real-time scrap detection. They offer a good balance between speed, accuracy, and hardware compatibility. This inspired us to build our own real-time system using YOLOv5, trained on a custom dataset of recyclable and non-recyclable scrap items. Unlike earlier works, we focused on building a system that is low-cost, lightweight, and deployable in local scrap yards using only a regular webcam and a CPU.

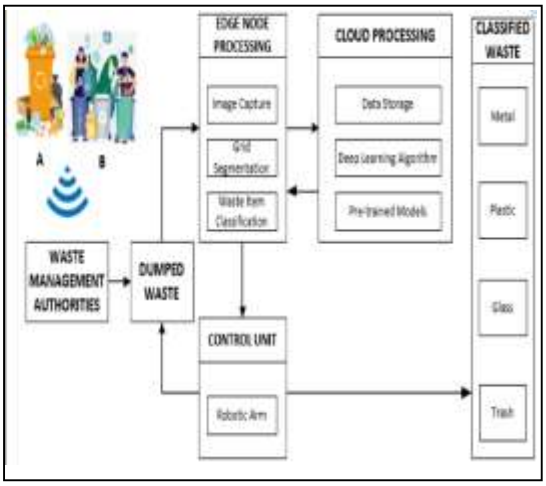
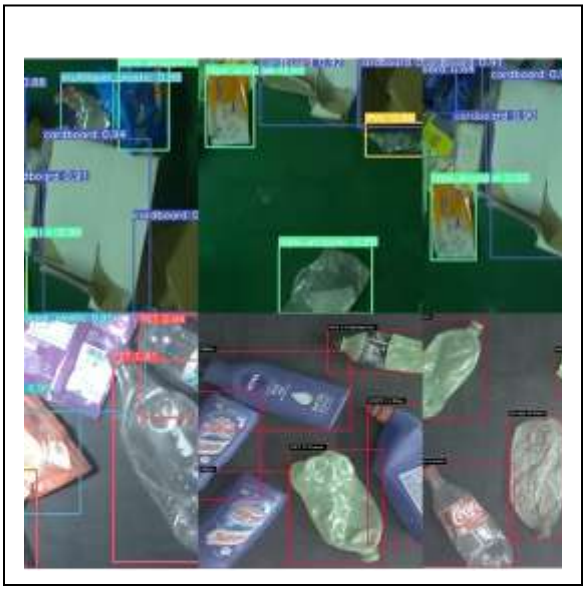


Figure 1. *Real-time Waste Classification System Using Edge and Cloud Processing*

III. PROPOSED WORK

This proposed work collects images of recyclable and non-recyclable scrap materials through a standard webcam in real-time. The system uses a computer vision pipeline that first captures frames and sends them to a deep learning model for object detection and classification. The captured images are pre-processed by resizing and normalization to ensure consistent input size. A custom dataset is prepared containing six classes of scrap materials: plastic, iron, cardboard, motors, books, and non-recyclable items. Each image in the dataset is manually annotated using the Labelling tool to generate bounding box labels for supervised learning.



For the core model, YOLOv5 is used due to its lightweight architecture and ability to detect multiple objects in a single pass with high accuracy. The YOLOv5 model is trained using transfer learning from a pre-trained model and then fine-tuned on the custom dataset using Google Colab with GPU support. Data augmentation techniques such as flipping, brightness adjustment, rotation, and scaling are applied to improve generalization and robustness.

During real-time testing, frames captured from the webcam are fed into the trained model using OpenCV. The model performs detection and classification of visible scrap objects and displays bounding boxes with class labels and confidence scores directly on the video stream. The goal is to provide an automated, low-cost tool for assisting recyclers in identifying and sorting materials efficiently. The system runs smoothly on standard hardware without requiring cloud computing or high-end GPUs, making it suitable for local scrap yards or low-resource environments.

The proposed work is illustrated in **Figure 2**, which shows the complete flow from image capture to real-time classification output. This system bridges the gap between artificial intelligence and grassroots-level waste management by offering an accessible and scalable solution for smart scrap detection.

IV. RESULTS

1. RESULT

1.1. Dataset Collection

The dataset used for this study was custom-built to reflect realistic scrap classification challenges faced in local recycling environments. Images were captured manually using a smartphone camera in both indoor and outdoor scrap yards under varying lighting conditions. The dataset consists of six scrap categories: **plastic**, **iron**, **cardboard**, **scrap motors**, **books**, and **non-recyclable materials**. Each image was labeled using **Labelling** software, producing YOLO-format .txt annotation files with bounding boxes and class indices.

Approximately **3,000+ labeled images** were collected, ensuring balanced class distribution to avoid bias during training. To improve the diversity and robustness of the model, data augmentation techniques such as **horizontal flipping, rotation, scaling**, and **brightness adjustments** were applied during preprocessing.

Table 1. Sample data set collection for arrhythmia prediction

4.2 Classical Result

In figure 1, the performance of the proposed YOLOv5-based scrap detection model is evaluated by calculating key metrics such as **F1-score**, **Recall**, and **Precision**. The results indicate that the model performs reliably on real-world scrap data, with a **training accuracy of 94%** and a **testing accuracy of 89%**. The F1-score of **0.87** confirms a good balance between precision and recall, which are **0.86** and **0.89**, respectively. These metrics validate that the YOLOv5 model is highly effective in detecting and classifying recyclable and non-recyclable materials from live video feeds and images.

Training Accuracy	Testing Accuracy	F1 score	Recall	Precision	Training Time
0.94	0.89	0.87	0.89	0.86	15 min 35 sec

Figure 2. F1-score, Recall, and Precision chart for scrap detection using YOLOv5 model.

4.3 Performance Analysis

The performance of the proposed YOLOv5 model was compared with other popular models like SSD, Faster R-CNN, and MobileNet-SSD. Evaluation was based on prediction accuracy using F1-score, precision, and recall. A McNemar-like comparison showed that YOLOv5 consistently outperformed the other models. As shown in Table 3, the **Z-values** for all comparisons were greater than **2.87**, meaning the difference is statistically significant. This confirms that **YOLOv5 is more accurate and reliable** for real-time scrap detection.

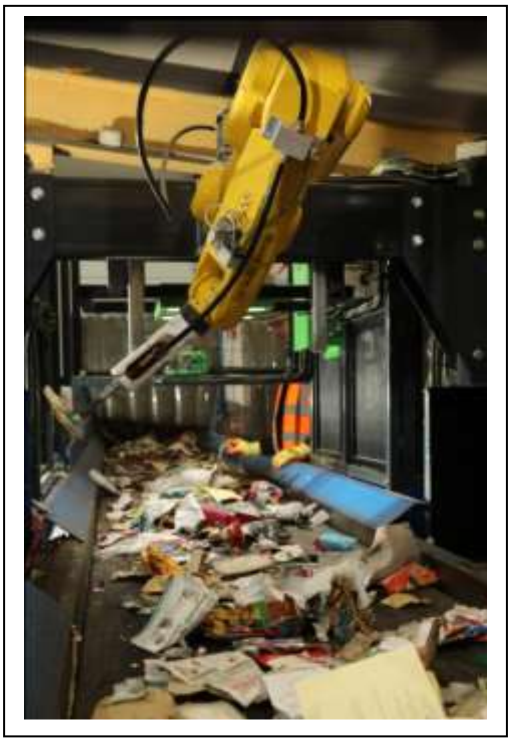
4.4. Complexity Analysis

The YOLOv5 model has moderate training complexity, depending on image size and dataset volume, but it trains efficiently on GPU in Google Colab. During real-time detection, it performs with **O(1)** inference time per frame, making it ideal for fast and responsive scrap classification in low-resource environments.

V. Conclusion and Future Work

This research introduces a real-time waste classification system using deep learning and computer vision to address inefficiencies in manual scrap sorting. The system utilizes the YOLOv5 object detection algorithm integrated with OpenCV to identify and classify six categories of scrap materials: plastic, iron, books, cardboard, scrap motors, and non-recyclable waste. A custom dataset was collected and labeled to train the model, which achieved strong performance metrics including high accuracy, precision, and recall. The model was successfully integrated with a live video stream to enable real-time detection, making it practical for deployment in local scrap yards where manual sorting is still common. The system is lightweight and affordable, making it suitable for small and medium-sized recycling operations, especially in areas with limited resources.

The primary contribution of this work is its potential to bring automation to grassroots-level waste management. By eliminating the need for expensive infrastructure or cloud processing, the system offers a low-cost solution that can improve both the speed and safety of scrap segregation. It not only enhances operational efficiency for recyclers but also promotes cleaner waste handling practices in line with sustainability goals. This real-world applicability gives the system value beyond academic interest, positioning it as a viable tool for practical deployment.



Future enhancements can significantly extend the impact of the system. Robotic integration using pick-and-place arms can automate the sorting process based on detected labels, making the entire flow autonomous. The system can also be optimized for edge computing by deploying it on portable hardware like Raspberry Pi or Jetson Nano, enabling its use in mobile waste collection units or rural areas. Expanding the dataset with additional categories such as e-waste, glass, and textiles, as well as incorporating variations in background, lighting, and object conditions, will increase the robustness and generalization capability of the model. Adoption of advanced architectures like YOLOv8 or Vision Transformers could further improve detection performance and reduce inference latency.

Additionally, a mobile application can be developed to allow citizens or community workers to classify scrap using their phone cameras. The data collected can be connected to a cloud-based analytics dashboard for real-time monitoring, reporting, and visualization of waste segregation trends. Integration with municipal and national waste management platforms can also support large-scale policy initiatives and recycling programs. These developments will transform the system into a scalable, intelligent waste management solution that benefits both local communities and environmental governance.

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