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Automated Waste Classification Using YOLOv11: A Deep Learning Approach for Sustainable Recycling

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Abstract
The rapid increase in waste generation due to urbanization and population growth has necessitated more efficient waste management solutions. Traditional waste sorting methods rely on manual labor, which is time-consuming, error-prone, and inefficient at large scales. This paper proposes an automated waste classification system using YOLOv11, the latest iteration of the YOLO family, which is known for its high speed and accuracy in object detection. By leveraging a custom dataset containing 10,464 labeled waste images from various categories—such as biodegradable, plastic, metal, paper, and glass—this study trains and evaluates a deep learning model capable of real-time waste identification and categorization. Experimental results demonstrate that YOLOv11 achieves high detection accuracy, with an overall classification accuracy of 94% and a mean average precision (mAP) exceeding previous methods. The model effectively differentiates between various waste types, though some misclassifications occur, particularly between visually similar materials like transparent plastic and glass. Performance metrics, including precision and recall, indicate the robustness of the proposed system in real-world applications. This research highlights the potential of YOLOv11 for integration into smart waste management systems, such as automated sorting machines and AI-powered recycling bins, to enhance efficiency and reduce environmental impact. Future work will focus on optimizing model performance by incorporating additional training data, applying advanced image augmentation techniques, and exploring hybrid approaches such as texture analysis and spectral imaging to improve classification accuracy. The implementation of this technology is expected to streamline waste recycling processes, minimize contamination in recyclable materials, and contribute to sustainable waste management practices.

Keywords: Waste Classification; YOLOv11; Deep Learning; Object Detection; Recycling; Sustainable Waste Management
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1.0 INTRODUCTION

The rapid increase in urbanization and population growth has escalated waste production, posing significant challenges for effective waste management and recycling processes (Sesay & Fang, 2025). Traditional manual sorting methods are labor-intensive and error-prone, which has driven research toward automated solutions (Olawade et al., 2024). Recent advances in deep learning have revolutionized object detection, offering robust tools for real-time classification tasks (Trigka & Dritsas, 2025). Among these, the YOLO (You Only Look Once) family of algorithms stands out due to its speed and accuracy, making it ideal for real-time applications such as autonomous vehicles, medical diagnostics, and surveillance systems. Its ability to balance speed and precision has established YOLO as a leading algorithm in both research and practical implementations (Ali & Zhang, 2024).

YOLOv11 introducing optimized architectures that enhance feature extraction, enabling detailed image analysis for applications such as real-time object detection, instance segmentation, and pose estimation (Khanam et al., 2025). The YOLOv11 object detection method improves its performance through the optimization of a loss function that includes three main components: distributed focus loss, bounding box regression loss, and class probability loss. The optimization is performed by integrating these three components and applying optimization algorithms to improve the accuracy and efficiency of the model in object detection tasks (He et al., 2024).

In this work, we present an automated waste classification framework that leverages YOLOv11 to accurately identify and categorize various waste items from images. A custom dataset was compiled and preprocessed, and the model was trained following established guidelines for custom data adaptation . Experimental results confirm that the proposed method not only improves detection accuracy but also offers a viable solution for integrating automated waste classification into existing recycling systems.

These advancements highlight the potential of deep learning-based object detection in addressing critical environmental challenges, particularly in waste management and recycling. By integrating YOLOv11 into an automated waste classification framework, this study contributes to the development of efficient and scalable solutions that can enhance sorting accuracy and streamline recycling processes. The findings of this research demonstrate the feasibility of implementing AI-driven waste classification in real-world applications, paving the way for more sustainable and technologically advanced waste management systems.

2.0 LITERATURE REVIEW

The YOLOv11 model has undergone rapid development and is applied in various fields of object detection, ranging from license plate recognition to waste management. One of the early applications of this model was in real-time vehicle license plate detection and recognition, which showed improved accuracy in identifying characters compared to previous methods, as well as being able to work efficiently under various lighting conditions and image capture angles (Vempati, 2024). Another study showed the use of YOLOv11 for traffic sign detection in Indonesia, where road conditions and sign diversity require robust and accurate models to improve driving safety (Pradana et al., 2024). In addition, YOLOv11 is also used in the field of ecology, specifically in bird detection for the purposes of wildlife monitoring, flight safety, and ecological studies. With a more advanced architecture, including a transformer-based backbone and an adaptive attention mechanism, the model achieves high precision in bird detection even in complex environments and variable lighting (Elef et al., 2025). Not only in bird detection, YOLOv11 has also been applied in the fisheries sector to identify fish species caught by traditional boats (canoe). Another study explored the use of this model in improving the accuracy and efficiency of fish species identification as part of a more sustainable fisheries management effort. With a dataset of 2,000 images of various local fish species, YOLOv11 was able to achieve 94% detection accuracy, with 92% precision and 90% recall. In addition to high accuracy, the study also highlighted the advantages of YOLOv11 in real-time image processing, allowing fishermen and fishery managers to make faster decisions related to the species caught (Tall et al., 2024).

YOLOv11's ability to detect small objects is also utilized in quality inspection of the leather industry, where the model aims to improve quality control in the leather industry. Traditional inspection methods have limited accuracy (70-85%), leading to significant material wastage. By using a controlled light chamber, this study achieved a detection accuracy of 93.5% for grubs defects and 91.8% for suckout defects on the flesh side, which is much higher compared to the grain side. The key findings show that flesh-side analysis can reveal defects that are more difficult to detect on the grain side, as well as improve metrics such as F1-Score, Precision, and Recall. This research highlights the importance of addressing defects on the flesh side that are often overlooked, providing a promising approach to optimize the utilization of leather in industrial applications, as well as potentially reducing waste and improving quality control in the production of leather goods (Banduka et al., 2024).

In addition to applications in industry and ecology, YOLOv11 also plays an important role in the medical field, especially in blood cell detection through microscopic images. In a study to classify different types of blood cells with a mean Average Precision (mAP) of 93.8%, which significantly improved the speed and accuracy of hematology analysis (Sazak & Kotan, 2024). Applications of YOLOv11 in the health sector also include fracture detection in X-ray images, where the model achieved an mAP of 96.8% with Intersection over Union (IoU) of 92.5%, far surpassing other models such as Faster R-CNN and SSD (Wei et al., 2025).

In addition to its use in healthcare, YOLOv11 was also explored for detecting defects in solar panels, which showed improved performance over previous versions and other machine learning methods. In this study, the YOLOv11-X algorithm provided excellent results with a precision value of 89.7%, recall of 87.7%, mean average precision (mAP) of 92.7%, and F1 score reaching 90%. This research uses three main types of datasets, namely thermal images to detect hotspots, optical images to identify defects on the panel surface, as well as an augmented version of the thermal dataset to improve the accuracy of the model. The results show that YOLOv11-X is more efficient in detecting defects than traditional algorithms such as SVM and Faster R-CNN. The superiority of YOLOv11 in detecting defects makes it a highly suitable technology to be applied in real-time monitoring systems based on edge devices, which can reduce operational costs and increase efficiency (Ghahremani et al., 2025). The application of YOLOv11 in the healthcare sector shows that this model can be used for tasks that require high precision and fast analysis.

In the agricultural sector, research conducted by Sapkota et al. (2024) showed that the YOLOv11 model has superior capabilities in detecting and counting the number of apples in a complex orchard environment. The study compared the performance of various YOLO object detection models, including YOLOv8, YOLOv9, YOLOv10, and YOLOv11, using a dataset consisting of 1,147 annotated apple images, obtained through smartphone cameras and machine vision sensors. The results show that YOLO11n has the best accuracy in counting apples. The application of YOLO technology in fruit detection not only contributes to the improvement of agricultural efficiency, but also proves its ability to handle objects of diverse shapes and sizes, including in the context of waste classification, which has non-uniform and complex characteristics. These findings further strengthen the potential of YOLOv11 as a superior solution in various fields that require automatic and accurate object detection and classification (Sapkota et al., 2024).

In the context of waste management, various studies have evaluated the performance of YOLO in detecting and classifying waste to improve the efficiency of recycling systems. For example, research to explore the application of YOLOv11 in waste segmentation at recycling facilities in Australia, showed that this model can improve the accuracy of waste detection and classification compared to traditional methods. With datasets covering various waste categories such as plastic, paper, and metal, the study found that artificial intelligence-based automation can reduce reliance on manual labor and improve the efficiency of the recycling process (Das et al., 2024). In addition, another study applied artificial intelligence to evaluate the physical stability of a mine waste storage facility in Chile. Although these studies focused on environmental risk monitoring, the use of AI in waste analysis shows great potential in improving the efficiency of industrial waste risk evaluation and mitigation. With the YOLOv11-based approach, the analysis process becomes faster and more accurate, while reducing reliance on manual labor and minimizing the possibility of human error. In addition, this technology offers high scalability and flexibility in various environmental conditions, allowing the system to adapt to changing waste characteristics as well as dynamic industry needs (Hermosilla et al, 2025).

From these studies, it can be seen that YOLOv11 has been applied in various fields that require fast and accurate object detection, including in the waste management sector. With advantages in inference speed and high accuracy, YOLOv11 has great potential to improve efficiency in automated waste classification and processing. The application of this technology in sustainable recycling can help reduce waste contamination as well as improve the quality of recyclables, making it a promising solution for more efficient and environmentally-friendly waste management.

3.0 METHODOLOGY

The methodological process used in this research can be understood by looking at Figure 1 below, which illustrates systematically the main stages carried out in data processing and model training for automatic waste classification.

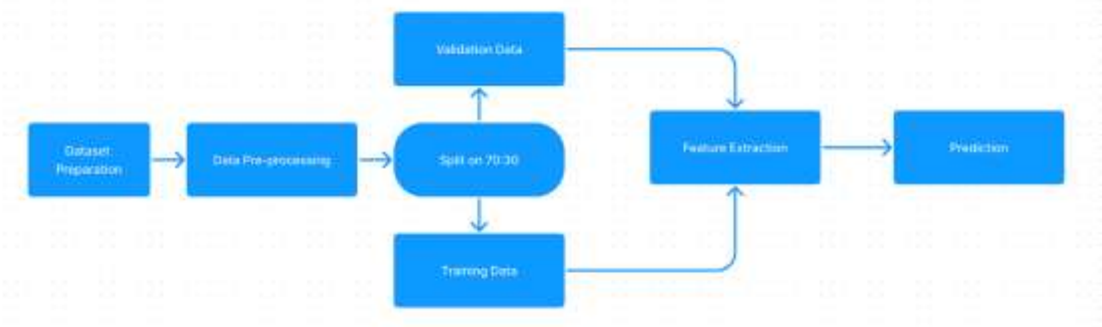

Figure 1. Methodology

Figure 1 shows the process flow used in this research to automatically classify waste using YOLOv11. The first stage is Dataset Preparation, where waste images are collected and labeled according to categories such as biodegradable, plastic, paper, metal, and glass. Next, Data Preprocessing is performed to improve image quality, including resizing, normalizing colors, and adding image variations to make the model more accurate. Data pre-processing is an important step to improve classification accuracy before it is used in machine learning (Afrianty et al., 2022). In addition, pre-processing is also required to ensure the dataset is free from negative elements such as noise, missing values, inconsistent data and redundant data. This stage aims to clean the data from irrelevant information so as to improve the quality of the input used in the machine learning process (Samah et al., 2020). After that, the dataset is divided into Training Data (70%) and Validation Data (30%) to ensure the model can learn and test well. In the Feature Extraction stage, YOLOv11 is used to recognize the unique patterns and characteristics of each type of waste. Feature extraction can be defined as the process of extracting the most representative information from raw data, aiming to minimize the variability of patterns within classes while increasing the variability of patterns between classes (Mohamad et al., 2015). To this end, YOLOv11 extracts a set of features from the litter images that help distinguish one category from another more accurately. Finally, the feature extraction results are used in the Prediction stage, where the trained model determines the waste categories more accurately, thus supporting more efficient and sustainable recycling efforts.

Data Set

The dataset used in this study consists of 10,464 data samples, which are divided into 7,324 train data, 2,098 validation data, and 1,042 test data. This dataset was obtained from the Roboflow Universe platform, which provides a collection of waste classification data that has been systematically labeled. This data includes various waste categories, such as biodegradable, plastic, paper, metal, and glass. Allowing the model to learn to distinguish between the types of waste more accurately. With a large amount of data and a balanced distribution of datasets, the deep learning model used, YOLOv11, can be optimally trained to improve performance in automatic classification of waste.

YOLOv11

YOLOv11 is the latest version of the YOLO (You Only Look Once) family of algorithms designed for real-time object detection with high speed and accuracy (Khanam & Hussain, 2024). YOLO is one of the Convolutional Neural Network (CNN)-based object detection models known for its ability to detect objects in real-time with high accuracy (Alif, 2024). YOLOv11, as the latest version in this series, builds on the foundation introduced by YOLOv1. Introduced at the YOLO Vision 2024 (YV24) conference, YOLOv11 brings significant advancements in object detection technology. With a more advanced architecture and a more optimized training method, this model offers improvements in terms of speed, efficiency, and accuracy in detecting various objects.

The innovative design of YOLOv11 incorporates advanced feature extraction techniques, enabling the capture of more nuanced details while maintaining a lean parameter count. One of the key improvements in YOLOv11 over its predecessor is the use of transformer-based feature extraction, which allows the model to capture more contextual information from the image. This results in improved accuracy across a wide range of computer vision (CV) tasks, from object detection to classification (Khanam & Hussain, 2024). In addition, YOLOv11 achieves a remarkable improvement in processing speed, which substantially enhances real-time performance capabilities (He et al., 2024).

In addition, YOLOv11 uses adaptive anchor-free detection, which reduces the dependency on anchor box selection and improves the detection capability of objects of various sizes (Elef et al., 2025). In this study, YOLOv11 is applied for automatic waste classification. The model is trained using a customized dataset that includes various waste categories, such as plastic, paper, metal, and glass. Experiments were conducted to evaluate the performance of YOLOv11 in terms of detection accuracy, inference speed, and computational efficiency. The results obtained were compared with previous methods to assess the superiority of this approach in improving the effectiveness of automated waste sorting systems.

4.0 RESULTS AND DISCUSSION

This research develops an automated system for classifying waste using the YOLOv11 model. This model is designed to recognize and differentiate various types of waste, such as glass, plastic, metal, paper, and biodegradable materials, with the aim of supporting a more efficient and sustainable recycling process. The developed system has been tested with various types of waste and shows good performance in detecting and classifying objects in images.

The model is able to recognize objects with high accuracy in most cases, but there are some challenges, especially with objects that have visual similarities, such as clear plastic and glass or recycled paper and biodegradable materials. In addition, the model performance graph shows that during the training process, the error rate (loss function) continues to decrease, indicating that the model is successfully learning and understanding the patterns from the waste data used. Evaluation using metrics such as precision, recall, and mean average precision (mAP) shows that the model can provide fairly reliable predictions, although there are still some classification errors. The detection results of this study can be seen in Figure 2 below.

Figure 2. Detection Results

Figure 2, which shows how the YOLOv11 model successfully identified and labeled different types of waste, including glass, plastic, metal, and biodegradable. From the figure, it can be observed that the model is able to recognize objects with a fairly high level of confidence, as indicated by the probability scores listed on the bounding box of each object. In addition, the model is able to distinguish objects with varying degrees of transparency and color, especially in the glass and plastic categories. Then the graph of the performance evaluation results of the YOLOv11 model can be seen in Figure 3.

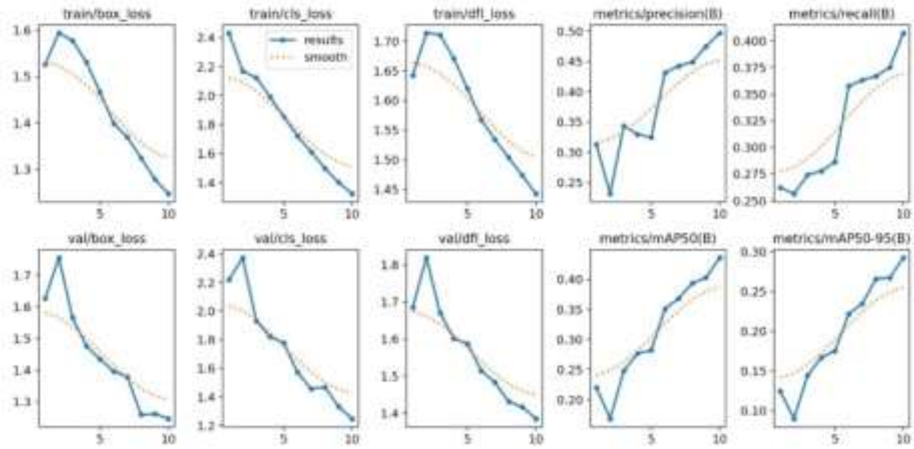

Figure 3. YOLOv11 Model Graph

Furthermore, Figure 3 presents the model performance evaluation graph based on loss and accuracy metrics during the training process. This graph shows that the box loss, classification loss, and distribution focal loss (DFL) values decrease consistently as the number of epochs increases, indicating that the model is getting better trained. On the other hand, evaluation metrics such as precision, recall, and mean average precision (mAP) show an increasing trend, indicating that the model is increasingly accurate in detecting and classifying waste objects in the test data. The results of the model performance from this research can be seen in Fig 4 below.

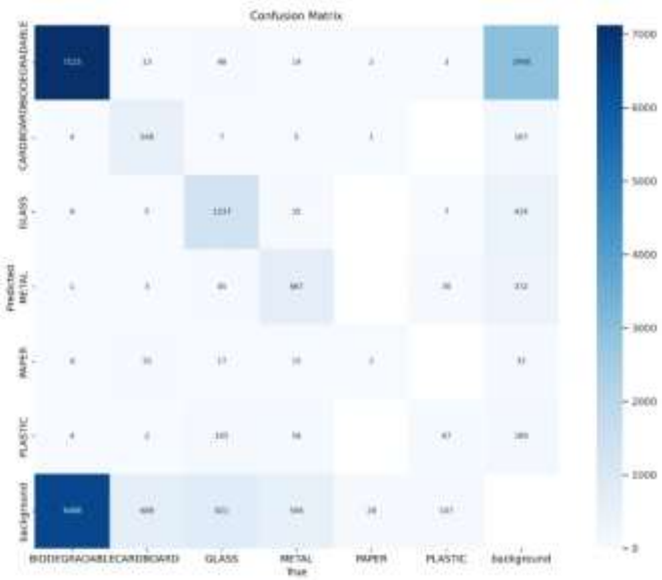

Figure 4. Confusion Matrix

Figure 4 displays the confusion matrix which shows the number of correct and incorrect predictions in each waste category. From this matrix, it can be seen that the model achieved a final accuracy of 94%, with most of the predictions being in the correct category. However, there are still some misclassifications, especially in distinguishing between glass and plastic. This errors are likely due to the visual similarity between categories, especially in lighting and shooting angle.

Based on the results obtained, the YOLOv11 model performed quite well in automatically detecting and classifying waste. However, there are still some challenges in distinguishing waste types that have similar visual characteristics. Improvements can be made by increasing the amount of training data, performing image augmentation, or using additional methods such as texture analysis and color spectrum to increase the accuracy of the model. This system has great potential to be applied in smart recycling systems, such as automated bins or AI-based waste sorting systems, which can help improve efficiency in the recycling process and support environmental sustainability.

5.0 CONCLUSION

This research has developed an automated system for waste classification using the YOLOv11 model. This model is designed to recognize and differentiate various types of waste, including glass, plastic, metal, paper, and organic materials, to support a more efficient and sustainable recycling process. The experimental results show that YOLOv11 is capable of detecting and classifying waste with a high accuracy level, reaching 94%.

Performance evaluation using metrics such as precision, recall, and mean average precision (mAP) shows quite reliable results, although there are still some classification errors, especially in distinguishing waste with similar visual characteristics, such as transparent plastic and glass, as well as recycled paper and organic materials. The analysis of the confusion matrix reveals that most predictions are accurate, but there is still potential for improvement in enhancing classification accuracy.

Several challenges identified in this study can be addressed by increasing the amount of training data, applying image augmentation techniques, and using additional methods such as texture analysis and color spectrum to improve detection accuracy. With its advantages in speed and inference accuracy, YOLOv11 has great potential to be applied in smart recycling systems, such as automatic trash bins or AI-based waste sorting systems. The implementation of this technology is expected to enhance the efficiency of the recycling process and contribute to environmental sustainability.

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