WASTEWISE: AI-POWERED WASTE EDUCATION FOR ELEMENTARY STUDENTS USING YOLOV8 AND ESP32-CAM

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Abstract—*The growing volume of global waste poses a significant challenge for effective waste management, particularly in developing countries where awareness and practices around waste sorting remain limited. This study aims to enhance elementary school students' understanding and efficiency in sorting organic and inorganic waste using an interactive, AI-powered educational tool. The proposed system, WasteWise, integrates YOLOv8 for real-time object detection and ESP32-CAM for capturing waste images. A pre-test and post-test experimental design was conducted to assess students' performance before and after using the system. The results showed a notable improvement in sorting accuracy, increasing from 60% with manual sorting to 90% using the WasteWise system, alongside reduced sorting time. These findings highlight the system's potential not only as an automated waste classification tool but also as a cost-effective and engaging platform for promoting environmental awareness and digital literacy among young learners.*

Keywords: *wastewise, YOLOv8, ESP32-CAM, artificial intelligence.*

Abstrak—*Meningkatnya volume sampah global menjadi tantangan serius bagi pengelolaan sampah yang efektif, khususnya di negara berkembang di mana kesadaran dan kebiasaan pemilahan sampah masih terbatas. Penelitian ini bertujuan untuk meningkatkan pemahaman dan efisiensi pemilahan sampah organik dan anorganik di kalangan siswa sekolah dasar melalui alat edukasi interaktif berbasis kecerdasan buatan. Sistem yang dikembangkan, WasteWise, mengintegrasikan YOLOv8 untuk deteksi objek secara real-time dan ESP32-CAM untuk menangkap citra sampah. Penilaian dilakukan menggunakan desain pre-test dan post-test untuk membandingkan performa siswa sebelum dan sesudah menggunakan sistem. Hasil menunjukkan peningkatan signifikan dalam akurasi pemilahan, dari 60% dengan metode manual menjadi 90% dengan WasteWise, disertai dengan pengurangan waktu dalam proses pemilahan. Temuan ini menunjukkan bahwa sistem tidak hanya berfungsi sebagai alat klasifikasi sampah otomatis, tetapi juga sebagai media edukatif yang hemat biaya dan menarik untuk meningkatkan kesadaran lingkungan dan literasi digital di usia dini.*

Kata Kunci*: wastewise, YOLOv8, ESP32-CAM, kecerdasan buatan.*

INTRODUCTION

The rapid increase in global waste production poses significant challenges for effective waste management and segregation. According to the United Nations Environment Programme (UNEP), approximately 2.01 billion tonnes of waste were generated globally in 2020 alone, with only a small portion efficiently sorted and recycled (*Global Waste Management Outlook 2024 - Beyond an Age of Waste: Turning Rubbish into a Resource*, 2024).

This issue is further exacerbated in developing countries, where waste sorting efforts are hindered by limited infrastructure and a shortage of skilled human resources. In Indonesia, improper waste disposal habits remain a major obstacle, reflecting a lack of environmental awareness among the general public (Kumar Lilhore et al., 2024; Natalia Marpaung et al., 2022). As such, awareness campaigns must begin early—

especially at the elementary school level—to shape positive habits in managing waste.

Waste education in Indonesia has primarily been delivered through traditional classroom activities and simple educational games. These approaches aim to instill students with basic knowledge of organic and inorganic waste types and promote sustainable behavior (Apriyani et al., 2023; Gustiani & Anshori, 2021). However, the impact of these methods is often limited by their passive nature and lack of real-world interaction.

In parallel, technological advancements have introduced new possibilities for addressing waste segregation issues. Artificial Intelligence (AI) has demonstrated strong potential in automating waste sorting through image-based object detection. Deep learning models such as convolutional neural networks (CNNs) and YOLO (You Only Look Once) have shown high accuracy and speed in classifying waste in real time (Ghatkamble et al., 2022; W. Lin, 2021). However, previous systems using platforms like Arduino are often costly and impractical for educational settings (Wibysono et al., 2022).

To address this limitation, we developed WasteWise, an educational tool that integrates YOLOv8 and the cost-effective ESP32-CAM microcontroller to classify organic and inorganic waste in real time. This system not only automates the waste detection process but also serves as an engaging platform for students to learn through direct interaction with AI and Internet of Things (IoT) technologies (Bawankule et al., 2023; Urlamma et al., 2024; Zhao et al., 2024).

Despite the growing importance of environmental education, current methods remain insufficiently interactive and technologically integrated. Students often lack access to practical, real-time tools that reinforce classroom knowledge through experiential learning. This study addresses the gap by proposing an affordable, AI-powered educational solution to improve waste sorting awareness and operational efficiency among elementary school students.

MATERIALS AND METHODS

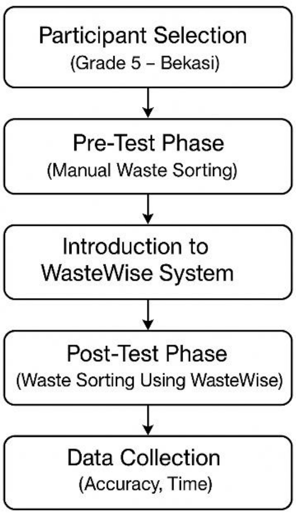
This section describes the rationale for technology selection and the system architecture used in this study. Recent studies highlight the growing role of artificial intelligence (AI) in education, emphasizing its capacity to promote essential skills such as computational thinking and digital literacy among elementary students (Abar et al., 2021; P. Lin et al., 2024). AI tools, including chatbots and machine learning-based activities, have been effectively applied to raise awareness and support interactive learning experiences (Kang et al., 2022; Sinha et al., 2023). In parallel, AI has also been successfully implemented in automated waste management using deep learning models like YOLO, which deliver fast and accurate object detection for real-time sorting (Fang et al., 2023; Zhao et al., 2024).

In this study, YOLOv8 was selected due to its improved speed, accuracy, and accessible documentation (Ultralytics, 2023). Combined with the low-cost ESP32-CAM, the system enables real-time waste detection with minimal hardware requirements (Viswanathan & Telukdarie, 2022). Furthermore, the platform serves as a hands-on educational tool that introduces Grade 5 students to AI concepts while promoting environmental awareness and sustainable behavior.

The WasteWise system integrates YOLOv8 for waste classification and Streamlit as the user interface. Images captured by the ESP32-CAM are transmitted to a laptop, where a Python-based detection script processes them and returns category labels (e.g., organic or inorganic), bounding boxes, and confidence scores. The interface provides real-time feedback and guides users to the appropriate waste bins. A confidence threshold is implemented to filter out uncertain predictions, ensuring reliable and accurate classification results. The system's modular software design also allows for seamless updates and independent operation.

This framework provides a low-cost, scalable solution that enhances both waste management practices and environmental education at the elementary school level.

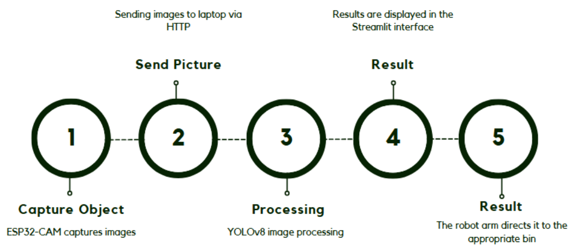
Participants and Study Design



Source : (Research Result, 2024)
Figure 1. Research Process Diagram

Figure 1 illustrates the overall research process. This study involved 20 students from

Grade 5 at a public elementary school in Bekasi, Indonesia. The participants were selected voluntarily based on interest and parental consent. All participants were actively enrolled in Grade 5 and had basic literacy and comprehension skills as inclusion criteria. The experiment followed a pre-test/post-test design, in which students first sorted waste items manually (pre-test), then performed the same task using the WasteWise system (post-test). Waste samples included common items such as plastic bottles, leaves, and food packaging. The accuracy and completion time were recorded and analyzed.



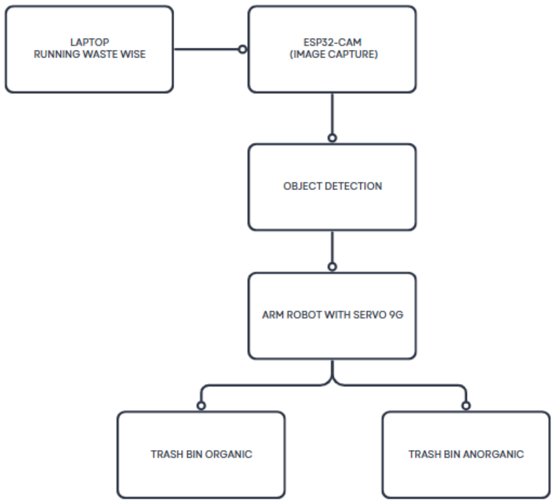
Source : (Research Result, 2024)

Figure 2. Software Architecture Diagram

Figure 2 presents the software architecture of the WasteWise system. The WasteWise hardware architecture is designed with minimal but essential components, ensuring a straightforward and efficient setup for rapid waste detection and classification. At the core of the system, the ESP32-CAM captures images of waste materials, which are then transmitted via Wi-Fi to a laptop for processing (as illustrated in Figure 6). Elementary school students place waste in front of the ESP32-CAM, which captures an image and sends it to the laptop. The laptop, acting as the primary processing unit, executes the detection algorithm, categorizing the waste as either "Organic" or "Inorganic." The results are displayed on the system interface, and students are guided to deposit the waste into appropriately colored bins.

To enhance system performance, a low-cost robotic arm has been integrated to assist in directing waste toward the correct bin. While the robotic arm lacks the capability to pick up waste, it raises its hand to indicate the correct bin ("Organic" or "Inorganic") based on the detection results. Once the classification is complete, the robotic arm activates, providing visual cues to guide students toward the appropriate bin. Although students still manually deposit the waste, the robotic arm aids the process by improving precision.

This integration of the robotic arm offers an affordable way to increase the system's interactivity, making it more engaging and user-friendly for elementary school students. It provides accurate guidance for waste disposal without introducing unnecessary complexity or high maintenance costs. The hardware design of the system is shown in Figure 3.



Source : (Research Result, 2024)

Figure 3. Hardware Architecture

RESULTS AND DISCUSSION

This research was conducted in two phases, namely pre-test and post-test, to evaluate the impact of the WasteWise system on improving elementary school students' understanding of sorting organic and inorganic waste.

The comparison between pre-test and post-test shows a clear improvement in students' performance. Manual sorting in the pre-test phase yielded an average accuracy of 60% with longer completion times (5–10 minutes), while post-test results using the WasteWise system reached 90% accuracy and faster completion (3–5 minutes), as shown in Table 1 and Table 2.

Post-test results indicated a significant improvement in both accuracy and efficiency. With the WasteWise system, students achieved an average accuracy of 90%, a substantial increase from their pre-test performance. Additionally, the time required for sorting was significantly reduced, as the system provided instant feedback on waste categories. Features such as adjustable image resolution and flashlight controls proved useful in adapting to environmental factors like poor lighting, ensuring consistent detection performance.

Table 1. Study Result

Aspect	PreTest (Manual)	PostTest (WasteWise)
Sorting Method	Manual, without tools	Using WasteWise tools
Amount of Waste Correct	Average 60%	Average 90%
Completion Time	5–10 minutes	3–5 minutes
Common Mistakes	Frequent Errors	Minimal Errors

Source : (Research Result, 2024)

Table 2. Study Result

Students Name	Total Waste Given	Total Waste Correct (Manual)	Total Waste Correct (Waste Wise)	Percentage Correct (Manual)	Percentage Correct (WasteWise)
Alif	10	9	10	90	100
Haura	11	5	10	45	91
Zara	11	9	10	82	91
Nayla	11	9	10	82	91
Raka	13	9	12	69	92
Fatih	15	9	13	60	87
Keysha	10	6	8	60	80
Naira	12	7	11	58	92
Ayla	14	10	11	71	79
Luqman	14	7	13	50	93
Farrel	13	6	12	46	92
Daffa	12	5	11	42	92
Rayyan	12	7	11	58	92
Yumna	11	5	10	45	91
Arka	13	7	12	54	92
Ghani	15	6	11	40	73
Shifa	15	5	14	33	93
Aqila	10	6	9	60	90
Zahra	10	8	9	80	90
Aldo	14	9	13	64	93
		Average %		60	90

Source : (Research Result, 2024)

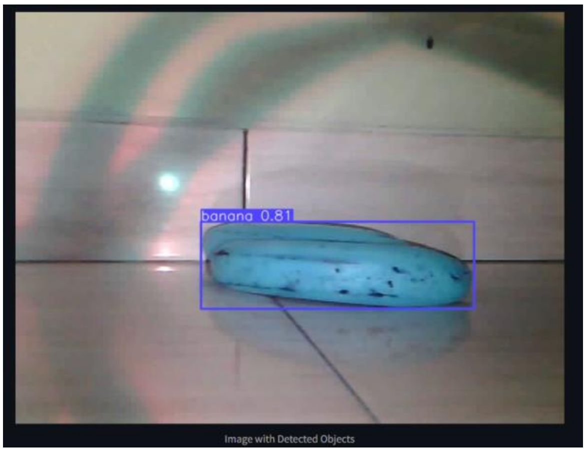
The visual instructions provided by the system also enhanced student engagement by offering clear, step-by-step guidance after detection. This not only increased their awareness of proper waste sorting but also allowed them to experience the practical application of technology in waste management.

These results demonstrate the effectiveness of the WasteWise system in improving students' awareness and ability to sort waste. By integrating AI and IoT technologies, the system reduced human error in sorting and provided an interactive, educational experience that introduced students to the basics of machine design and environmental responsibility.

The WasteWise system features a streamlined and intuitive interface developed using Streamlit, enabling users to connect the ESP32-CAM, select image quality, set detection confidence thresholds, and control the flashlight for low-light environments. Figures 4 and 5 demonstrate how the YOLOv8 model detects and classifies objects in real time, while Figure 6 illustrates the resulting output with bounding boxes and waste labels.

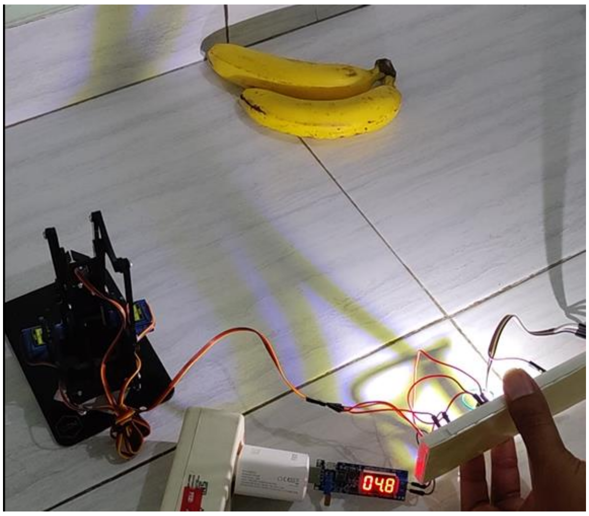
Source : (Research Result, 2024)

Figure 4. Capture Object



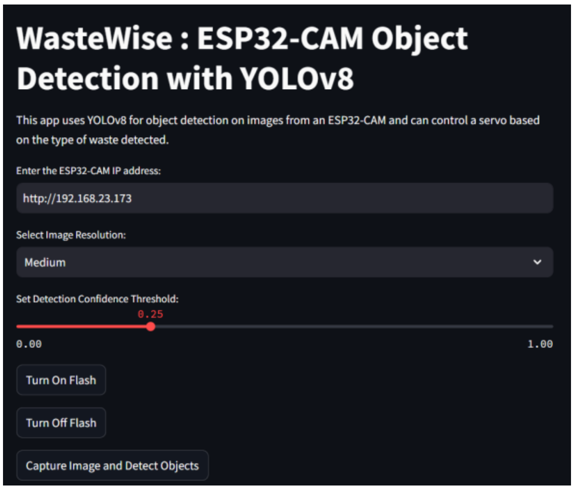
Source : (Research Result, 2024)

Figure 5. Result Detection Object



Source : (Research Result, 2024)

Figure 6. Result Detection Object



Source : (Research Result, 2024)
Figure 7. User Interface

The user-friendly dashboard (Figure 7) enhances the educational experience by displaying categorized results in tabular form, providing clear, actionable feedback. These visual components validate the system's operational readiness and suitability for classroom environments, bridging technology with hands-on learning.

The WasteWise system has proven to be an effective tool for raising awareness about waste sorting among elementary school students. By integrating YOLOv8 and ESP32-CAM technology, it not only simplifies the waste classification process but also provides a fun and engaging learning experience.

A comparison between manual sorting during the pre-test and automated sorting in the post-test using the WasteWise tool showed significant improvements in both accuracy and efficiency. Students' accuracy increased from 60% during manual sorting to 90% with the assistance of the system, while sorting time was reduced from 5–10 minutes to just 3–5 minutes. These results highlight the system's ability to streamline the waste sorting process and minimize human error.

These results are consistent with findings from previous studies involving AI-based waste classification. (Sai Susanth et al., 2021) demonstrated that convolutional neural networks (CNNs) significantly improved waste classification accuracy, particularly when dealing with diverse waste images in real-world scenarios. Similarly, (Bawankule et al., 2023) reported high real-time detection performance using YOLOv8, achieving over 90% accuracy in object recognition tasks. However, both studies were conducted in industrial or laboratory settings. In contrast, the present study applies similar AI technologies—YOLOv8 and ESP32-CAM—within a classroom environment, offering not only an effective solution for waste sorting but also a practical, hands-on learning platform. This demonstrates the dual potential of such systems to support environmental education and technological literacy among elementary school students.

The system's interactive interface played a key role in boosting students' confidence in sorting waste. It provided clear and straightforward instructions, enabling students to separate and dispose of waste correctly. Beyond improving their understanding of waste segregation, this hands-on implementation also familiarized students with the practical applications of AI and IoT technologies.

The modular design of the system ensures flexibility, allowing each component, such as YOLOv8 and Streamlit, to operate independently and be updated seamlessly. Features like adjustable image resolution and customizable confidence thresholds make the system adaptable to various environmental conditions, including low-light settings. Furthermore, the use of ESP32-CAM, an affordable hardware platform, makes it suitable for educational environments.

However, the system relies on a stable Wi-Fi connection for real-time processing, which may pose challenges in areas with poor connectivity. Expanding the system to include additional waste categories and implementing offline functionality could further enhance its usability. Additionally, incorporating adaptive learning could enable the algorithm to refine its classification capabilities over time.

The WasteWise system not only enhances waste sorting in schools but also introduces students to modern technologies, fostering environmental awareness and digital literacy. By integrating this dual focus into the curriculum, schools can address immediate educational objectives while equipping students with skills essential for navigating an ever-evolving technological landscape.

CONCLUSION

The WasteWise system presents an innovative solution for integrating artificial intelligence into elementary school education to support sustainable waste management. By combining YOLOv8 for real-time object detection and ESP32-CAM for image capture, the system effectively identifies and classifies waste into organic and inorganic categories.

The experimental results showed a significant improvement in student performance, with an increase in sorting accuracy from 60% to 90%, and a reduction in sorting time from 10 minutes to 3 minutes. These findings support the integration of AI into the elementary education curriculum as a technology-based active learning strategy, enhancing both environmental awareness and digital literacy.

While the system proved effective in a real school setting, limitations include reliance on stable internet connectivity and a narrow range of detectable waste types. Future developments should aim to expand waste categories, implement adaptive feedback, improve energy efficiency, and enhance connectivity.

Overall, WasteWise has strong potential as a scalable, low-cost educational tool that promotes sustainability, hands-on learning, and AI literacy in early education.

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