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Real-time color-based sorting and counting system for plastic bottle caps using esp32 and tcs3200 sensor

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ABSTRACT

Plastic waste has become a major environmental issue due to its increasing generation and the limited effectiveness of waste management systems. In recycling activities, sorting plastic materials by color is essential because it influences both the quality and economic value of recycled products. However, plastic bottle caps in waste banks and small-scale recycling facilities are still commonly sorted manually, making the process labor-intensive, time-consuming, and often inconsistent. This study presents an embedded system for real-time sorting and counting of plastic bottle caps based on color using an ESP32 microcontroller and a TCS3200 color sensor. The developed system integrates a conveyor mechanism, five servo motors, five infrared sensors, and a 16×2 LCD functioning as a human–machine interface. Plastic bottle caps were classified into five color categories: red, yellow, green, blue, and white. System performance was evaluated through 500 integrated experimental trials, with each color category tested 100 times. During each trial, color detection, object sorting, counting, and data visualization were performed simultaneously. The TCS3200 sensor correctly identified 487 out of 500 samples, resulting in an average accuracy of 97.4%. No counting errors were observed during the experiments, yielding 100% accuracy for the infrared-based counting system, while all servo actuations operated successfully throughout the testing process. The counting values displayed on the LCD were fully consistent with the readings obtained from the infrared sensors. These findings indicate that low-cost embedded components can be effectively integrated to support automated sorting and counting applications. The developed system offers a practical solution for waste banks and small-scale recycling facilities and may contribute to improving operational efficiency and promoting sustainable plastic waste management.

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1. INTRODUCTION

The problem of plastic waste is a major global environmental challenge that requires effective and sustainable management solutions, particularly in high-producing countries like Indonesia (Balestra & Bellopede, 2022; Phelan et al., 2022; Zhang et al., 2022). To mitigate this issue, the application of the Reduce, Reuse, and Recycle (3R) concept is the main strategy, wherein recycling activities aim to extract the economic value of used materials (Maddalene et al., 2023; Prabawati et al., 2023; Raharjo et al., 2018; Shekdar, 2009).

In the recycling industry and waste bank, the process of sorting waste by color is an important stage because it affects the quality of recycled products and the selling value of products. Plastic bottle caps are a type of waste that has high economic potential because the material can be reprocessed into various new products (Chindasiriphan et al., 2025; Mansour et al., 2025).

However, the process of sorting plastic bottle caps is generally still done manually. This method requires a large amount of labor, a relatively long time, and a high level of concentration to maintain the consistency of the sorting results (Hanifah & Arumsari, 2020; Hidayat et al., 2026). In addition, direct contact with waste has the potential to pose a health risk to workers (Fontaine et al., 2026). Therefore, automation of the sorting process is needed to improve the operational efficiency and economic value of plastic waste (Liu et al., 2024).

The development of embedded system technology allows the process of object identification, decision-making, and mechanical control to be carried out automatically with a high degree of accuracy (Farjana et al., 2023; Suvarnamma & Pradeepkiran, 2021). ESP32 microcontrollers are widely used in embedded systems because they have good processing capabilities, low power consumption, and easy integration with various sensors and actuators (Morchid et al., 2024; Nur-A-Alam et al., 2021; Taiwo et al., 2022).

Several previous studies have developed automatic sorting systems using color sensors, proximity sensors, and digital image processing (Vetricha Wulandari, 2020). TCS3200 color sensors have been widely used for color identification in a variety of applications, such as fruit classification and sorting of industrial objects (Imanuel et al., n.d.; Juliano et al., 2020; Sari et al., 2018). However, a critical comparison reveals a significant research gap: existing architectures predominantly focus on isolated tasks. For instance, studies by Imanuel et al. and M. I. Sari et al. succeeded in performing basic color identification, but they lacked multi-channel mechanical segregation and real-time quantitative tracking features. Most previous research has still focused on color identification or object sorting separately and has not integrated color detection, automatic sorting, and object enumeration functions in a single, integrated embedded system.

In addition, research that specifically addresses the sorting of plastic bottle caps using multi-servo and infrared sensor-based enumeration systems at the scale of waste banks and small recycling industries is still limited. This condition shows the opportunity to develop a low-cost automation system that can improve the efficiency of plastic waste management.

The system is designed to recognize five color categories of plastic bottle caps, namely red, yellow, green, blue, and white. Each color category relates to a single servo actuator to direct the object towards the appropriate container. Infrared sensors are used to calculate the number of objects that have been successfully sorted so that the sorting and enumeration process can be carried out automatically and in real-time.

The novelty of this research lies in the synchronization and integration of a TCS3200 color sensor, five servo actuators, and five infrared sensors in one low-cost embedded system. Unlike previous research that generally only focused on isolated color identification or object sorting, the proposed system is capable of simultaneous color detection, physical multi-channel sorting, and real-time recording of the number of objects in one integrated platform with minimal computational delay.

The main contributions of this research include: (1) the development of an ESP32-based plastic bottle cap sorting system and TCS3200 sensor, (2) the integration of an object enumeration system using infrared sensors, and (3) the implementation of a low-cost embedded system to support the automatic management of plastic waste in waste banks and small-scale recycling industries.

The system test was carried out using 500 integrated test scenarios consisting of five color categories, namely red, yellow, green, blue, and white, with each category tested 100 times. In each test, the performance of the TCS3200 color sensor, infrared sensor, and servo motor was evaluated simultaneously to assess the overall reliability of the system.

Therefore, the purpose of this study is to design and evaluate a sorting system and a plastic bottle cap counter based on a TCS3200 color sensor and an ESP32 microcontroller that can work in real-time. The evaluation of the system is carried out through the measurement of color detection accuracy, object enumeration accuracy, and servo actuation accuracy. The results of this research are expected to be a low-cost automation solution to support more effective and sustainable plastic waste management.

2. RESEARCH METHOD

2.1 Research Design

This research uses the Research and Development (R&D) method with an embedded system design and implementation approach for automatic sorting and enumeration of plastic bottle caps based on color. The research stages include literature review, hardware and software design, system integration, performance testing, data analysis, and research report preparation. The experimental procedures were carried out systematically and sequentially, starting from cleaning and preparing the bottle cap samples, placing objects at the starting point of the conveyor, the color scanning process, mechanical directing by the servo arms, to automatic recording as the objects passed the infrared sensors.

The literature study stage was carried out to examine the technology of TCS3200 color sensors, ESP32 microcontrollers, infrared sensors, servo motors, and object sorting automation systems. Furthermore, hardware and software design, integration of all components, and system testing are carried out to evaluate the performance produced. All tests were conducted under constant maintained room lighting conditions to minimize environmental influences on color sensor readings.

2.2 Hardware Configuration and Specification

The proposed embedded system consists of an ESP32 microcontroller, a TCS3200 color sensor, five servo motors, five infrared sensors, a DC motor-driven conveyor, and a 16×2 LCD. The ESP32 acts as the main controller that processes sensor data and coordinates system operations.

The TCS3200 sensor detects the color of plastic bottle caps and sends the acquired data to the ESP32 for classification. Based on the classification result, the corresponding servo motor is activated to direct the object into the appropriate container. Infrared sensors count the number of objects entering each container, while the LCD displays the counting results in real time as a human–machine interface (HMI).

The hardware configuration and integration of all system components are illustrated in Figure 1, while the specifications of the hardware components used in this study are presented in Table 1.

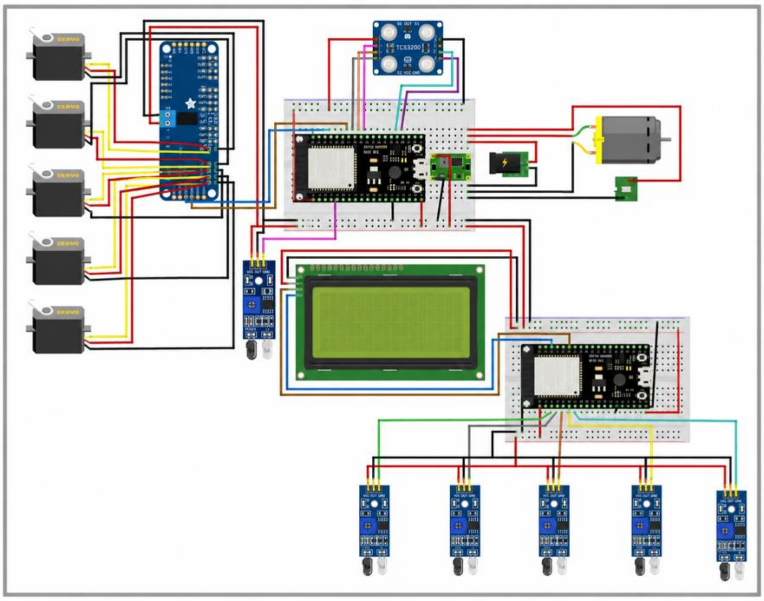

Figure 1 Hardware configuration of the proposed system

Table 1 Hardware Specifications Used in the Proposed System

No	Components	Specification	Function
1	ESP32	Dual-core 240 MHz, Wi-Fi/Bluetooth	Main system controller
2	TCS3200 Color Sensor	RGB color sensor	Detects the color of plastic bottle caps
3	SG90 Servo Motor	Operating voltage: 4.8–6 V	Directs objects to the corresponding sorting bin
4	Infrared Sensor	Obstacle detection sensor	Counts the number of sorted objects
5	LCD 16×2 I2C	I2C interface display	Displays counting results in real time
6	DC Motor	Operating voltage: 12 V	Drives the conveyor system
7	Conveyor Belt	Belt conveyor mechanism	Transports objects through the system

a. ESP32 Microcontroller

The ESP32 is used as a system control center because it has high data processing capabilities, low power consumption, and an adequate number of input/output pins to connect various sensors and actuators.

b. TCS3200 Color Sensor

The TCS3200 color sensor is used to detect the color of plastic bottle caps based on the intensity of red, green, and blue components. This sensor consists of an array of photodiodes equipped with RGB color filters and transparent filters. When light hits the surface of the object, some of the light is reflected towards the sensor. The intensity of the received light is then converted into a frequency signal which is processed by ESP32 to determine the color category of the object. Prior to the experimental trials, a sensor calibration procedure was performed to identify and map the specific frequency ranges for the five target colors (red, yellow, green, blue, and white). This process involved exposing the TCS3200 sensor to reference samples of each colored bottle cap under constant lighting conditions. The microcontroller then recorded the specific minimum and maximum frequency values of the R, G, and B components for each color, which were subsequently used to establish the threshold parameters for the color classification algorithm

In this study, the TCS3200 sensor was employed to recognize five color categories of plastic bottle caps: red, yellow, green, blue, and white. The sensor is mounted in a fixed position to maintain the consistency of color reading. The test object is a plastic bottle cap with a diameter of about 28 mm.

c. Infrared Sensor

The system uses five infrared sensors mounted on each output path. The sensor functions to calculate the number of bottle caps that have successfully entered the sorted container. The sensor works based on the change in the state of logic when the object passes through the detection area.

d. Motor Servo

The system uses five servo motors as the object sorting actuator. Each servo is in charge of directing the bottle cap to the container according to the color classification results. The servo mapping on the system is shown as follows: Servo 1 for Red, Servo 2 for Yellow, Servo 3 for Green, Servo 4 for Blue, Servo 5 for White.

e. System Conveyor

The conveyor is driven using a DC motor to move the plastic bottle caps continuously towards the detection and sorting area. The use of conveyors allows the sorting process to take place automatically and continuously.

2.3 Software Design

The software was developed using the Arduino IDE and programmed in C/C++ language. The developed algorithm controls the operation of the embedded system, including color detection, object sorting, counting, and real-time data visualization.

The system operation can be described as follows: (a) The system initializes all sensors and actuators. (b) The DC motor drives the conveyor to transport plastic bottle caps. (c) The TCS3200 sensor detects the color of the object. (d) The ESP32 processes the sensor data and classifies the object color using an RGB range thresholding algorithm. This algorithm compares the proportions of the R, G, and B component readings that fall into specific numerical minimum and maximum boundary intervals previously defined for each basic color. (e) The corresponding servo motor receives a control signal from the ESP32. (f) The object is directed to the appropriate sorting bin. (g) The infrared sensor counts the object entering the bin. (g) The counting result is displayed on the LCD in real time. (h) The system returns to the initial state and waits for the next object. This process is continuously repeated, enabling the system to perform real-time color-based sorting and counting of plastic bottle caps automatically.

2.4 Testing Scenarios

The test is carried out to evaluate the system's performance in detecting colors, sorting objects, and calculating the number of objects automatically. The test used five color categories of plastic bottle caps, namely red, yellow, green, blue, and white. Each category is tested 100 times so that the total test reaches 500 test scenarios.

In each test scenario, the color sensor TCS3200 identify the color of the object, the servo motor sorts according to the classification results, and the infrared sensor calculates the number of objects entering the container. Thus, the evaluation of color sensors, infrared sensors, and servo motors is carried out simultaneously in a single system operating cycle.

a. Color Sensor Accuracy Testing

The accuracy of the color sensor was calculated using Equation (1):

$$Accuracy\ (color) = \frac{N_{correct}}{N_{total}} x\ 100\%$$

with:

$N_{correct}$ = Correct amount of color detection.

N_{total} = Total Tests

2.4.2 Infrared Sensor Accuracy Testing

The accuracy of the infrared sensor is calculated using the Equation (2):

$$Accuracy\ (IR) = \frac{C_{correct}}{C_{total}} x\ 100\%$$

with:

$C_{correct}$= Number of objects calculated correctly

C_{total} = Actual number of objects.

2.4.3 Servo Motor Accuracy Testing

The accuracy of the servo motor is calculated using the Equation (3):

$$Accuracy\ (servo) = \frac{S_{correct}}{S_{total}} x\ 100\%$$

with:

$S_{correct}$= Number of successful servo actuations

S_{total} = Total Tests.

A test is declared successful if the servo moves to the specified position and the object enters the appropriate container.

2.5 Data Analysis

The test results were analyzed descriptively quantitatively using the parameters of color sensor accuracy, infrared sensor accuracy, and servo motor accuracy. The total testing in this study amounted to 500 integrated test scenarios that included simultaneous performance evaluation of TCS3200 color sensors, infrared sensors, and servo motors. Test results are presented in the form of tables and graphs to facilitate data interpretation and evaluate the overall performance of the system.

3. RESULTS AND DISCUSSIONS

3.1 System Implementation

The proposed embedded system for sorting and counting plastic bottle caps was successfully implemented according to the designed architecture. The system consists of an ESP32 microcontroller, a TCS3200 color sensor, five servo motors, five infrared sensors, a DC motor-driven conveyor, and a 16×2 LCD functioning as a human–machine interface (HMI).

During operation, plastic bottle caps are transported by the conveyor to the color detection area. The TCS3200 sensor acquires the color information of the object and transmits the data to the ESP32 for classification. Based on the classification result, the corresponding servo motor is activated to direct the object into the appropriate sorting bin. After the object enters the bin, the infrared sensor detects and counts the object automatically. The counting results are subsequently displayed on the LCD in real time, allowing users to monitor the sorting process continuously.

The implementation results demonstrate that all hardware components operate properly and perform color detection, object sorting, counting, and data visualization in an integrated real-time system.

3.2 Experimental Setup

System performance was evaluated using five color categories of plastic bottle caps, namely red, yellow, green, blue, and white. Each color category was tested 100 times, resulting in a total of 500 integrated experimental trials.

In each trial, the TCS3200 sensor performed color recognition, the servo motor executed object sorting, the infrared sensor counted the sorted object, and the LCD displayed the counting results. Therefore, all system components were evaluated simultaneously within a single operational cycle.

3.3 Performance Evaluation of the TCS3200 Color Sensor

The color recognition performance of the TCS3200 sensor is presented in Table 2.

Table 2 Accuracy of the TCS3200 Color Sensor

Color	Number of Tests	Correct Detections	Accuracy (%)
Red	100	99	99
Yellow	100	96	96
Green	100	97	97
Blue	100	100	100
White	100	95	95
TOTAL	500	487	97.4
Sample Variance (s^2)			4.30^2
Standard Deviation (s)			2.07

The statistical evaluation reveals that the integrated TCS3200 sensor achieved an impressive overall accuracy of 97.40%. To further validate the system's consistency, descriptive and inferential statistical analyses were performed. The computed sample variance ($s^2 = 4.30$) and standard deviation ($s = 2.07$) demonstrate low dispersion across the five color categories, indicating highly stable sorting performance across different light wavelengths. Furthermore, the 95% confidence interval analysis yields a narrow margin of error ($MoE = 1.39\%$), establishing the true system accuracy securely between 96.01% and 98.79%. This statistically implies that if the automated sorting process were to be replicated under identical environmental conditions, the classification success rate would consistently remain above 96%. This high level of precision highlights the reliability of using a single, low-cost ESP32 platform to synchronize real-time multi-channel optical segregation without requiring complex or high-cost computing architecture.

3.4 Performance Evaluation of the Counting System

The counting system consists of infrared sensors and a 16×2 LCD used for real-time visualization. The system was evaluated by comparing the actual number of objects with the counted values displayed on the LCD. The results of the counting system evaluation are shown in Table 3.

Table 3 Accuracy of the Counting System

Color	Number of Tests	Correct Count	Accuracy (%)
ir 1	99	99	100
ir 2	96	96	100
ir 3	97	97	100
ir 4	100	100	100
ir 5	95	95	100

The average counting accuracy was calculated as:

$$\text{Accuracy Ir (avg)} = \frac{(99+96+97+100+95)}{487} = 100\%$$

The counting system correctly counted all detected objects during the experiments, resulting in an accuracy of 100%, demonstrating high reliability in object counting operations.

Furthermore, the values displayed on the LCD were fully consistent with the readings obtained from the infrared sensors, confirming that the LCD can reliably provide real-time information to users.

3.5 Performance Evaluation of Servo Motors

Servo motors were employed as sorting actuators to direct plastic bottle caps into the corresponding bins. The performance evaluation results are presented in Table 4.

Table 4 Accuracy of Servo Motor Operation

Color	Number of Tests	Successful Operations	Accuracy (%)
Servo 1	99	99	100
Servo 2	96	96	100
Servo 3	97	97	100
Servo 4	100	100	100
Servo 5	95	95	100

The average servo accuracy was calculated as:

$$\text{Accuracy Servo (avg)} = \frac{(99+96+97+100+95)}{487} = 100\%$$

The results demonstrate that the servo motors operated reliably in directing objects to the appropriate bins.

3.6 Discussion

Experimental evaluation showed that color detection, sorting, and counting could be performed simultaneously within a single embedded platform. The system achieved reliable performance in all operational stages, indicating its suitability for automatic plastic bottle cap sorting applications.

Color recognition using the TCS3200 sensor reached an average accuracy of 97.4%, indicating its suitability for bottle cap sorting applications. When compared with previous studies, this accuracy level shows a significant efficiency improvement. For example, research by M. I. Sari et al. (2018) using the TCS3200 was limited to sorting three basic color objects without a quantity data accumulation system, whereas Vetricha Wulandari (2020) integrated macro waste automation but the detailed sorting accuracy of similar materials was not maximized**.** The highest accuracy was obtained for the blue bottle cap, while the white bottle cap exhibited the lowest accuracy. This difference is likely attributed to variations in surface reflectance characteristics, which influence the intensity of reflected light captured by the sensor. Highly reflective surfaces may introduce fluctuations in RGB measurements and consequently affect classification performance.

The counting system, consisting of infrared sensors and LCD visualization, achieved an average accuracy of 100%. The results indicate that infrared sensing is highly effective for object counting in conveyor-based sorting systems. In addition, the consistency between infrared sensor readings and LCD outputs confirms the reliability of the human–machine interface for real-time monitoring.

Similarly, the servo motors achieved an average operational accuracy of 100%, demonstrating stable and reliable actuation during object sorting. The absence of sorting failures indicates that the synchronization between sensing, processing, and actuation was successfully implemented in the proposed embedded system.

By integrating ESP32, TCS3200, infrared sensors, servo motors, and an LCD display, the proposed system provides a practical and low-cost solution for automated plastic bottle cap sorting. The proposed system has significant potential for implementation in waste banks and small-scale recycling facilities to improve plastic waste management efficiency.

3.7 Limitations and Future Work

Although the proposed system demonstrated promising performance, several limitations should be acknowledged. First, the system was evaluated using only five color categories of plastic bottle caps, namely red, yellow, green, blue, and white. Therefore, its performance for additional colors or mixed-color objects remains unexplored. Second, all experiments were conducted under controlled indoor lighting conditions. Variations in ambient illumination may affect the reflectance properties of objects and influence the performance of the TCS3200 color sensor.

Third, the experiments were performed using a laboratory-scale prototype with a limited number of samples. Consequently, the long-term reliability and scalability of the system in industrial environments have not yet been evaluated. Finally, the color classification method relies on predefined threshold values, which may limit the adaptability of the system under varying environmental conditions. Future research may investigate the performance of the system under different lighting conditions and evaluate additional color categories and recyclable materials. The integration of adaptive classification methods based on machine learning or computer vision may further improve color recognition accuracy and system robustness.

Moreover, Internet of Things (IoT) technology can be incorporated to enable remote monitoring, data logging, and real-time system management. Large-scale experiments in actual recycling facilities are also necessary to assess the operational reliability and throughput of the proposed system in practical applications.

4. CONCLUSION

This study presented the design and implementation of an embedded system for real-time sorting and counting of plastic bottle caps using an ESP32 microcontroller and a TCS3200 color sensor. By integrating color detection, object sorting, counting, and data visualization into a single platform, the developed system was able to perform automated operations in real time.

System performance was evaluated through 500 integrated experimental trials involving five color categories: red, yellow, green, blue, and white. The evaluation included simultaneous testing of the TCS3200 sensor, infrared sensors, servo motors, and LCD display within a single operating cycle. Color recognition using the TCS3200 sensor achieved an average accuracy of 97.4%. In addition, the infrared-based counting system and servo actuators operated with 100% accuracy during the experiments.

The consistency between infrared sensor readings and LCD outputs indicates that the system can provide reliable real-time information for users. These findings suggest that low-cost embedded components can be effectively integrated to support automated sorting applications with high reliability.

Although the system was developed specifically for plastic bottle caps, its architecture may be adapted for other recyclable objects with similar physical characteristics. The findings highlight the feasibility of applying low-cost embedded automation in waste banks and small recycling facilities. Such systems may contribute to more efficient and sustainable plastic waste management practices.

Theoretically, this study contributes to the field of embedded automation by demonstrating the efficient integration of real-time color classification and object counting on a single, low-cost microcontroller. Practically, this system offers an affordable and adaptable solution for local waste banks and small recycling facilities, helping them improve sorting accuracy, streamline operations, and support broader circular economy practices.

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