Smart Coffee Bean Sorting: A Deep Learning Approach with Pneumatic Ejection Mechanism

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Abstract

In the food processing industry, particularly in the cultivation and processing of coffee, classifying coffee beans to select those of high quality that meet standards in terms of ripeness and size is a critical step that significantly influences the final product quality. In this study, we develop a coffee bean sorting model based on a pneumatic system integrated with artificial intelligence. The process operates as follows: Robusta coffee beans are fed into a hopper and passed through a vibrating conveyor to separate and evenly distribute them into slots. The beans then pass through the camera system and are identified based on color and size. Non-standard beans, such as those smaller than the specified size or lighter in color, are flagged for removal. These beans are located and tracked. The pneumatic valve system is then activated and removed from the production line. The test results show that the YOLOv11 model achieves an average accuracy of 99% at an IoU threshold of 0.5 (mAP@50) and 90% above an IoU threshold of 0.5 to 0.95 (mAP@50:95). This shows that the model can detect and classify defective coffee beans with high accuracy. After the identification process, the pneumatic removal system also demonstrated a classification accuracy of approximately more than 90%.

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Keywords
Coffee bean; Sorting machine; Deep learning; Classification

1. Introduction

Coffee is one of the most widely consumed beverages worldwide. More than just a drink, coffee reflects changing consumer behavior, place-based experiences, and emerging values such as ethical consumption. While previous studies have focused on coffee consumption in developed markets of the Northern Hemisphere, coffee has recently become a global beverage. This has prompted research into coffee tourism in diverse contexts today. Therefore, a deeper exploration of how coffee connects consumption activities with tourism and culture is warranted [1]. Ensuring the quality of raw materials before processing is essential to maintain common standards and the safety of the final product. This directly affects consumer satisfaction. This principle is widely applied in the cereal food industry, where objective and reliable quality assessment methods are essential. For example, beans are evaluated through subjective visual inspections that often yield inconsistent and ineffective results [2]. However, advances in machine vision and sensors today offer many advantages for accurate grain quality assessment [3]. With the increasing application of science and technology in agriculture, data-driven approaches play an important role in improving and assessing product quality. GrainSet is a machine vision-based image database of wheat, corn, sorghum, and rice collected from multiple countries. This resource supports automated quality inspection, facilitates grain storage and trading, and promotes AI-based smart agriculture [4]. By integrating advanced technology into agriculture, Karmakar et al. explored hyperspectral imaging (HSI) combined with few-shot learning (FSL) to overcome the limitations of traditional grain quality assessments. This method enables accurate, non-invasive, and real-time grain classification, even with minimal labeled data [5]. In addition to quality classification, researchers have focused on addressing food safety issues in grain production. A notable example is the application of a low-

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cost, portable device that uses fluorescence imaging to detect and classify aflatoxin-contaminated corn kernels. This non-invasive solution significantly reduced aflatoxin levels [6]. Hyperspectral imaging has emerged as a powerful tool for coffee variety discrimination in coffee identification. Combining spectral and spatial preprocessing techniques such as wavelet transform, and empirical mode analysis with support vector machine models allows the system to achieve classification accuracy above 80%, especially when using pixel-by-pixel spectral data [7]. Traditional manual methods are often labor-intensive and inconsistent. Therefore, Chang et al. introduced a deep learning-based method with up to 100% accuracy in identifying defective coffee beans [8]. Furthermore, hyperspectral imaging has been successfully applied to predict major aroma compounds in roasted coffee beans. This allows rapid and non-destructive screening of flavor characteristics [9]. Tan et al. proposed a novel, location-independent method for assessing green coffee bean quality based on the color characteristics of the bean coat. This approach allows for efficient, low-cost, and widely applicable quality assessment and helps detect origin-related fraud in the coffee industry [10]. In [11], the authors developed a YOLOv8n-based object detection model to identify and classify green coffee beans, focusing on detecting microscopic defects in coffee beans. By integrating advanced techniques such as WIoUv3, ECA, and C3Ghost, the proposed model achieved an impressive accuracy of 99. In a similar deep learning-based approach, Hassan et al. evaluated the performance of multiple pre-trained models for classifying coffee varieties. By applying models such as ResNet-50, EfficientNet, and DenseNet, the study achieved high accuracy and F1 scores close to 100% [12].

Motivated by the need for an efficient, objective, and scalable solution to coffee bean quality control, this research was conducted to address the limitations of manual inspection methods, which are often labor-intensive, inconsistent, and slow. By leveraging advances in AI and automation, we aim to develop an integrated system that ensures high-precision defect detection and sorting, thereby improving overall processing efficiency and product quality in the coffee industry. In this paper, we focus on the following key contributions:

- Developing a complete coffee bean sorting machine that integrates mechanical, pneumatic, and vision-based systems for automated quality control in coffee processing.
- Integrating AI-based object detection using the YOLOv11 model to classify coffee beans based on visual attributes such as color and size, achieving high detection performance (99% mAP@50, 90% mAP@50:95).
- Designing and implementing a pneumatic ejection mechanism capable of accurately removing defective beans with over 90% accuracy while preserving the quality of acceptable beans and demonstrating the system's practical performance with an estimated throughput of 8 kg/hour, confirming its applicability in real-world industrial environments.

The remainder of this paper is organized as follows: Section 2 presents the coffee bean sorting system and the applied deep learning model used for classification; Section 3 describes the experimental results evaluating the system's performance; finally, Section 4 concludes the paper by summarizing the main contributions and suggesting directions for future work.

2. Coffee Bean Sorting System and Applied Deep Learning Model

In this section, we present two key components that form the main key of our approach. First, we describe the design and operation of the coffee bean sorting system, followed by an explanation of the deep learning model integrated into the process.

2.1. Coffee Beaning Sorting System

The coffee bean sorting machine is designed to automate the identification and separation of defective beans based on color characteristics. Its primary purpose is to improve the efficiency and accuracy of quality control in coffee production using mechanical, vision-based, and pneumatic systems. The entire process is coordinated by a central Mitsubishi PLC controller, which ensures synchronized operation across all system components.

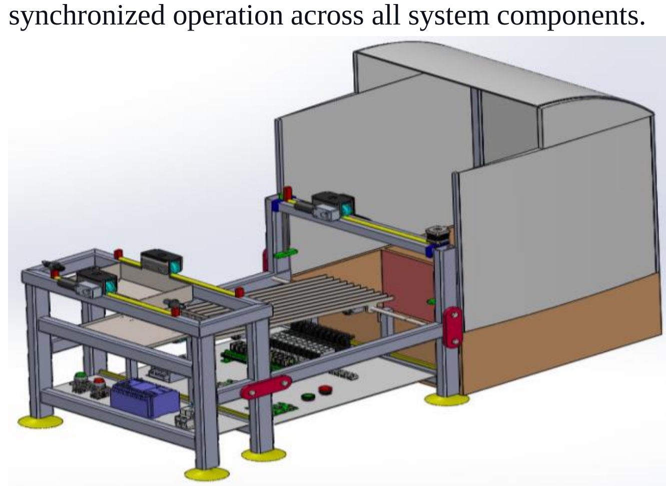


Figure 1. 3D model of the coffee bean sorting machine.

As illustrated in Fig. 1, the machine features a solid iron frame that houses the core modules. The structure supports a stable and durable operation environment suitable for continuous industrial use. The dimensions of the model are 80 cm in length, 30 cm in width, and 58 cm in height.

The process begins at the feeding hopper (Fig. 2), where raw coffee beans are loaded into the system. The hopper is equipped with a vibrating mechanism that helps the beans move steadily onto a grooved conveyor (Fig. 3). The vibration, combined with evenly spaced grooves on the conveyor, ensures that each bean is aligned and separated as it moves forward.

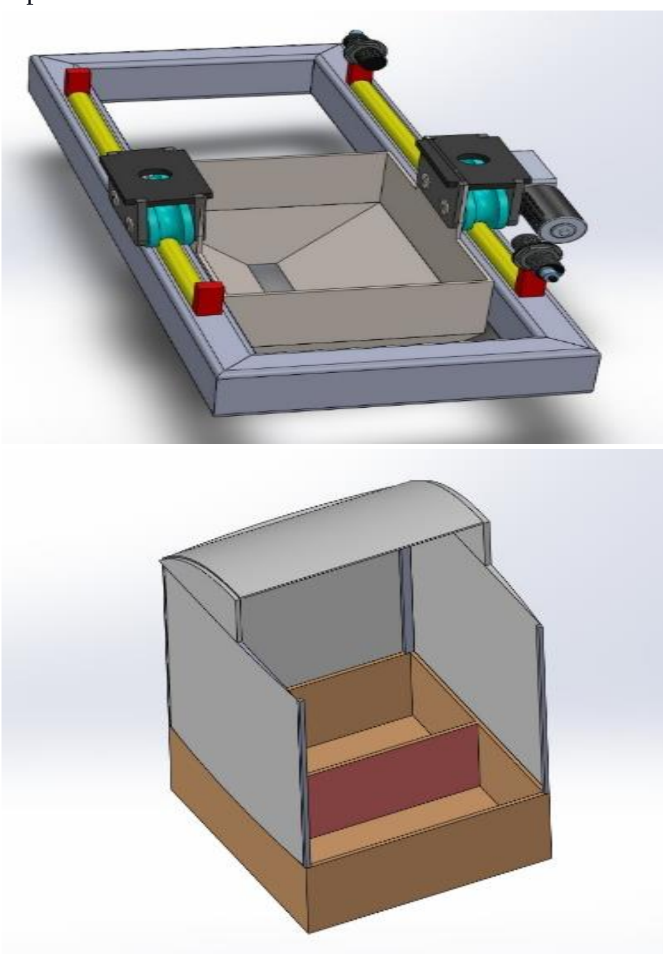


Figure 2. The initial feeding hopper and the bean collection bin after sorting.

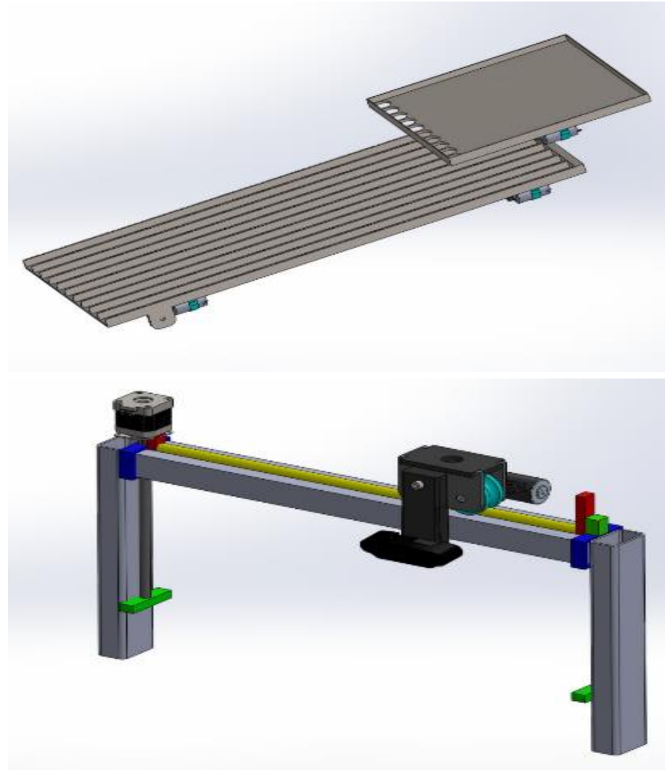


Figure 3. Vibrating conveyor and camera module.

Once the beans are correctly aligned, they pass beneath a camera module (also shown in Fig. 3), where each bean is scanned and classified in real-time using a pre-trained YOLOv11 object detection model. The model identifies defective beans that do not meet the required color or quality criteria and sends their coordinates to the control system.

Upon receiving this data, the system activates the pneumatic control unit (Fig. 4), which operates a series of air valves. These valves release targeted bursts of compressed air to eject the substandard beans into a separate collection bin (also visible in Fig. 2). This high-speed sorting method is precise and non-intrusive, preserving the quality of acceptable beans.

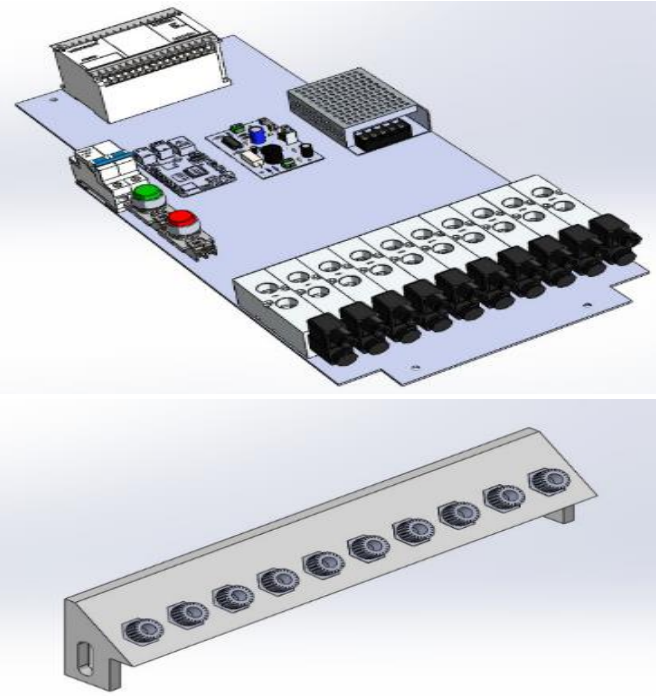


Figure 4. Pneumatic control unit and valves.

The machine operates through three main stages:

- The vibrating motor assists in feeding and spacing the beans.
- Image processing through a webcam and YOLOv11 model identifies each bean's quality.
- Pneumatic ejection removes defective beans from the production line.

Figure 5. Practical test model.

As shown in Fig. 5, the practical test model demonstrates the integration of all system components in real working conditions. The system supports two automatic modes, making it user-friendly and flexible for different operational needs. Additionally, understanding the pneumatic system—which includes air generation, storage, and distribution—is essential for ensuring the reliable performance of the sorting process.

In addition to performance, the Smart Coffee Bean Sorting system was designed with operational efficiency in mind. Thanks to its simple mechanical structure and pneumatic ejection mechanism, the system ensures low maintenance requirements and minimal operating costs. This makes it not only suitable for large-scale processing facilities but also accessible and cost-effective for small and medium-sized coffee producers. The machine achieves high sorting accuracy by effectively managing each step and integrating sensors and mechanical actuators while protecting the system from external disturbances. This comprehensive approach enables efficient and reliable industrial-scale coffee bean quality control operations.

2.2. Applied Deep Learning Model

Ultralytics YOLOv11 is the next iteration of the "You Only Look Once" (YOLO) model family, providing state-of-the-art performance on a variety of computer vision tasks such as object detection, segmentation, classification, pose estimation, oriented bounding box (OBB) detection, and real-time object tracking. The architecture of YOLOv11 is designed to simultaneously improve accuracy, reduce the number of parameters, accelerate inference, and enable scalable deployment across a wide range of model sizes [13].

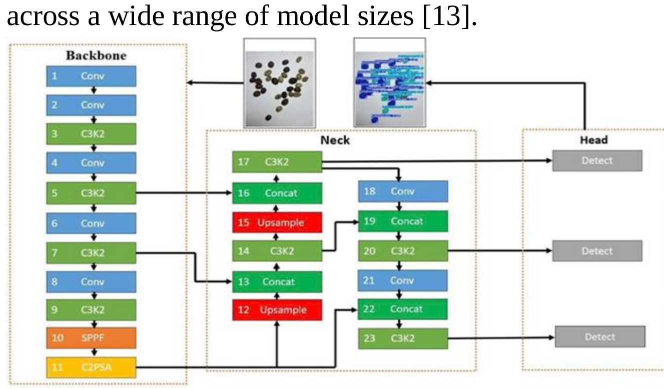


Figure 6. Applied Yolov11 Architecture.

In **Fig. 6**, we employed the YOLOv11 model to detect and classify coffee beans into two categories: high-quality beans (represented in black) and defective or low-quality beans (represented in other colors). The above model allows for accurately identifying individual coffee beans through input images. This process is essential to automate the quality control process in coffee production, ensuring consistency and reducing the reliance on manual inspection.

3. Experimental Results

To test the coffee bean sorting process directly on the model, 01 kg of coffee beans, including 80% qualified and 20% unqualified beans, are fed into the hopper. Then, the coffee beans are transferred to the conveyor belt equipped with evenly spaced grooves suitable for the coffee beans. The vibration motor operates so that the coffee beans are aligned and evenly spaced as they move along the path leading to the coffee bean identification through the camera.

As soon as the coffee beans pass through the camera system, each coffee bean is detected and classified by the pre-trained YOLOv11 model. Immediately after detection, the coordinates of defective beans that do not match the required color specification are identified. This information triggers pneumatic valves to eject the substandard beans into a separate collection area.

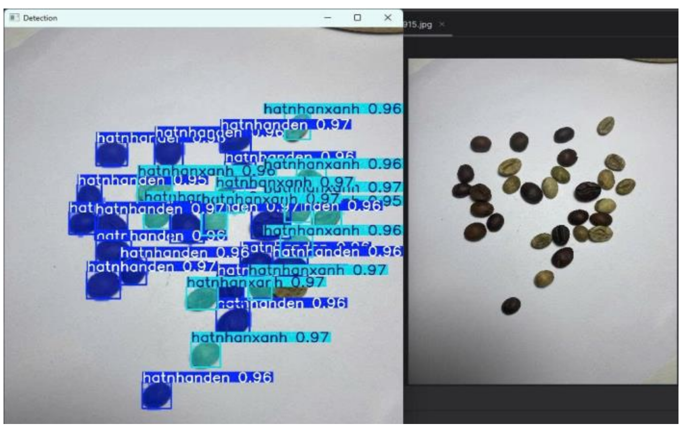
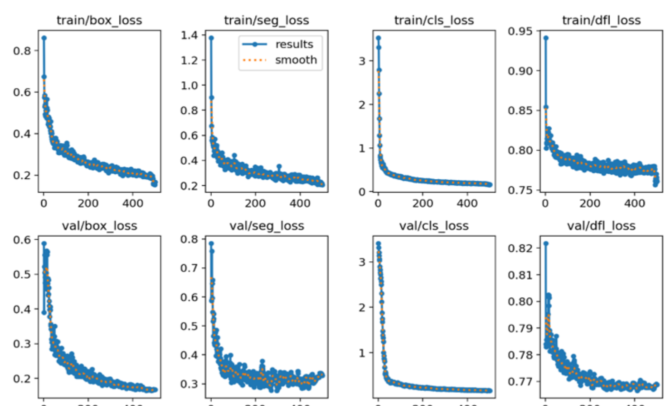


Figure 7. Coffee Bean Detection Results.



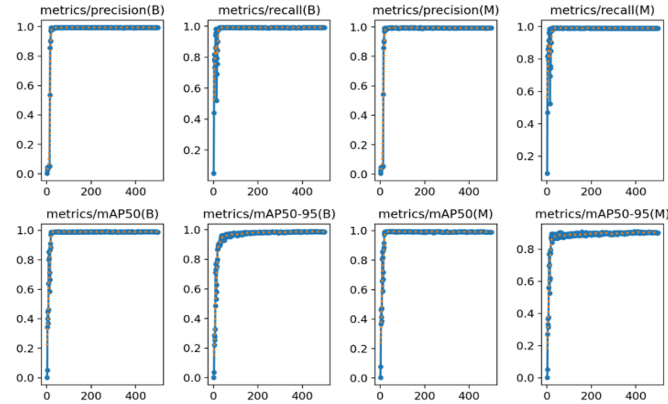


Figure 8. Training and Evaluation Curves.

To evaluate the performance of the detection and sorting system, we provided approximately 1 kilogram of Robusta coffee beans, equivalent to about 8,000 individual beans. The system was able to process the entire batch within approximately 8 minutes. The experiment was conducted over three shifts, each lasting 8 hours, to assess the system's stability and consistency during extended operation. Experimental results demonstrated that the YOLOv11 model achieved a mean Average Precision of 99% at IoU 0.5 (mAP@50) and 90% across IoU thresholds from 0.5 to 0.95 (mAP@50:95), reflecting both high detection accuracy and precise object localization.as shown in Fig. 7. Meanwhile, the pneumatic ejection mechanism successfully sorted the defective beans with an accuracy exceeding 90%.

The Fig. 8 shows how a deep learning model learns and improves over time when trained for object detection and segmentation. It tracks different types of loss (like how far off the model's predictions are) and accuracy measures (like how well it detects and segments objects) over many training steps. The losses gradually decrease, meaning the model learns better predictions. At the same time, accuracy scores go up quickly and stay high, showing the model performs exceptionally well. The training and validation results are similar, meaning the model learns well and works well on new, unseen data. Overall, the model is learning steadily and reliably throughout the training process.

4. Conclusion

Ensuring the quality of raw materials plays a vital role in maintaining the overall standard of food products, particularly in the coffee industry, where coffee beans' size and ripeness directly influenced flavour and commercial value. In this study, we developed and implemented an intelligent coffee bean sorting system that combined computer vision with a pneumatic ejection mechanism. Our approach automated the detection and classification of defective beans based on visual features such as colour and size—two key indicators of bean quality and ripeness.

In this paper, we tested 1 kg of coffee (about 8,000 beans) to evaluate the system's performance. The model achieved a mean accuracy (mAP) of 99% at an IoU threshold of 0.5 (mAP@50) and 90% when averaging over multiple IoU thresholds from 0.5 to 0.95 (mAP@50:95). In addition, the pneumatic classification model achieved an accuracy of more than 90%. The entire process was completed in less than 60 minutes.

These results confirmed that integrating deep learning algorithms with automatic classification technology has provided an effective solution for real-time quality control in coffee processing and makes it suitable for practical implementation. In the future, we aim to improve the system by incorporating additional quality criteria such as irregular shape and surface texture, while also increasing processing speed and adaptability to a wider range of grain types. To further enhance precision and versatility, advanced techniques such as texture sensors, geometric analysis, and AI-driven micro-defect detection will also be explored.

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Hệ thống phân loại hạt cà phê thông minh sử dụng mô hình học sâu và hệ thống khí nén

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Tóm tắt Trong ngành chế biến thực phẩm, đặc biệt là trong trồng trọt và chế biến cà phê, việc phân loại hạt cà phê nhằm chọn lọc những hạt đạt chất lượng cao, đáp ứng các tiêu chuẩn về độ chín và kích thước là một bước quan trọng, ảnh hưởng đáng kể đến chất lượng sản phẩm cuối cùng. Trong nghiên cứu này, chúng tôi phát triển một mô hình phân loại hạt cà phê dựa trên hệ thống khí nén tích hợp trí tuệ nhân tạo. Quy trình hoạt động như sau: hạt cà phê Robusta được đưa vào phễu chứa và đi qua băng tải rung để tách và phân bổ đều vào các rãnh. Sau đó, hạt di chuyển qua hệ thống camera và được nhận dạng dựa trên màu sắc và kích thước. Những hạt không đạt chuẩn, chẳng hạn nhỏ hơn kích thước quy định hoặc có màu nhạt hơn, sẽ được đánh dấu để loại bỏ. Các hạt này được định vị và theo dõi, sau đó hệ thống van khí nén sẽ được kích hoạt để loại bỏ chúng ra khỏi dây chuyền sản xuất. Kết quả thử nghiệm cho thấy mô hình YOLOv11 đạt độ chính xác trung bình 99% tại ngưỡng IoU 0.5 (mAP@50) và trên 90% trong khoảng ngưỡng IoU từ 0.5 đến 0.95 (mAP@50:95). Điều này chứng tỏ mô hình có khả năng phát hiện và phân loại hạt cà phê lỗi với độ chính xác cao. Sau quá trình nhận dạng, hệ thống loại bỏ các hạt không đạt chất lượng bằng khí nén cũng cho thấy độ chính xác phân loại đạt khoảng trên 90%.

Từ khóa Hạt cà phê; Máy phân loại; Học sâu; Phân lớp