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Research Article

Machine Vision for Quality Control in Halal Food Production: A Deep Learning Approach

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Abstract

Ensuring the quality and integrity of halal food products has become increasingly important with the growth of the global halal food industry. Conventional quality control methods, which rely on manual inspection and laboratory testing, are often time-consuming, subjective, and prone to human error. This study aims to develop and evaluate a machine vision system powered by deep learning algorithms to automate quality control processes in halal food production. A convolutional neural network (CNN)-based framework was implemented to classify and detect defects, contamination, and non-halal elements in food products. The system was trained using a dataset of 12,500 labeled images collected from halal-certified production facilities, with data augmentation applied to improve model generalization. Performance metrics, including accuracy, precision, recall, and F1-score, were used to evaluate the system. The results demonstrate that the proposed deep learning model achieved 96.8% classification accuracy, with high precision (95.5%) and recall (97.2%), significantly outperforming conventional machine vision techniques. The findings indicate that deep learning-driven machine vision can provide fast, reliable, and scalable quality control, supporting compliance with halal standards while reducing operational costs. This research highlights the potential of artificial intelligence to modernize quality assurance systems in halal food industries.

Keywords: Deep learning, Machine vision, Quality control

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INTRODUCTION

The global halal food industry has experienced significant growth in recent decades, driven by rising demand from Muslim consumers and increasing recognition of halal certification as a marker of quality and safety (Duane et al., 2024). This growth has been accompanied by heightened expectations for strict adherence to halal standards, which encompass not only the permissibility of raw materials but also hygienic handling, processing, and packaging. As halal food markets expand beyond Muslim-majority countries, the complexity of maintaining rigorous quality control across multinational supply chains has become a critical concern for producers and regulators alike.

Quality assurance in halal food production involves comprehensive inspection processes to verify the authenticity, cleanliness, and compliance of products (Prasad & Deswal, 2024). Traditional inspection methods rely heavily on manual labor and laboratory testing, which are often time-consuming, subjective, and susceptible to human error. Such limitations can compromise the reliability and efficiency of the quality control process, particularly in high-volume production lines where real-time decision-making is essential (Bontempi, 2017). Automation, data-driven inspection, and intelligent technologies offer an opportunity to address these limitations by enhancing consistency, speed, and precision in quality assurance.

Machine vision technology has emerged as a promising tool for food industry applications, enabling automated visual inspection for defect detection, contamination monitoring, and compliance verification (Lu et al., 2024). The application of machine vision in halal food production can potentially reduce the reliance on manual checks, ensuring that halal-certified products meet global quality standards. These developments highlight the importance of adopting advanced technologies, including artificial intelligence, to strengthen halal food quality management systems.

The halal food industry continues to face significant challenges in ensuring that products meet strict standards of cleanliness, authenticity, and integrity throughout the production process. Manual inspection remains the primary method of quality control, which is slow, expensive, and inconsistent due to variability in human judgment (Islam & Murakami, 2020). These limitations lead to delayed identification of quality issues, increased risk of non-compliance with halal regulations, and higher operational costs for producers.

The growing scale and complexity of halal-certified supply chains exacerbate these challenges. Multiple production sites, diverse raw materials, and different regional regulatory requirements increase the potential for quality lapses if control systems are not robust (Mahmud et al., 2023). The reliance on post-production testing and manual inspections cannot adequately address the demand for real-time monitoring, making it difficult to guarantee that products remain compliant from raw material intake to final packaging.

Advances in machine vision have shown potential in automating quality control in conventional food processing, but the specific application of these techniques in halal food production remains limited (Mahmud et al., 2023). Without adopting modern intelligent systems, producers risk inefficiencies, reduced competitiveness, and compromised consumer trust in halal-certified products.

This research aims to develop a machine vision system powered by deep learning algorithms for quality control in halal food production (Gouvea, 2012). The objective is to automate the detection of defects, contamination, and non-halal elements during the production process, ensuring real-time compliance with halal standards. The system is designed to classify and monitor products accurately using visual data, thereby reducing reliance on manual inspection.

The study also seeks to evaluate the performance of the proposed machine vision model through metrics such as accuracy, precision, recall, and F1-score (Di Salvo et al., 2017). By training a convolutional neural network (CNN) on a comprehensive dataset of halal-certified production images, the research intends to assess the system's ability to generalize across different product categories and processing conditions (Francke & Castro, 2013). The results will be compared with conventional image processing techniques to highlight the advantages of deep learning-based approaches.

The ultimate goal of this research is to provide a scalable, reliable, and cost-effective quality control solution that can be integrated into halal food production lines (Francke & Castro, 2013). The findings aim to demonstrate that deep learning-driven machine vision can significantly improve compliance monitoring while supporting operational efficiency.

Existing studies in food quality assurance have primarily focused on general applications of machine vision in defect detection, grading, and sorting (Wang & Dai, 2024). These studies demonstrate that automated systems outperform human inspection in terms of speed and consistency (Laurent et al., 2012). However, most of the research has been conducted in non-halal contexts, with limited attention to the unique requirements of halal food production, where ethical, religious, and hygienic considerations must be monitored simultaneously.

Previous applications of machine vision in halal industries are still in their infancy and largely rely on conventional image processing techniques, which have limited accuracy in complex environments (Thoma et al., 2018). These methods struggle to adapt to variations in lighting, texture, and contamination types, leading to inconsistent detection rates. Deep learning techniques, which have shown superior performance in visual recognition tasks, remain underexplored in this domain.

Very few studies incorporate an evaluation of deep learning models using large, diverse datasets obtained directly from halal-certified facilities. As a result, there is a lack of validated solutions that are capable of addressing the dynamic and context-specific challenges faced in halal production environments (Mersico et al., 2024). This research addresses that gap by introducing a robust, deep learning-based system designed for the halal food sector.

The novelty of this study lies in its integration of deep learning-based machine vision into halal food production for automated quality control (Trovato et al., 2020). Unlike earlier research that applies traditional vision systems, this study leverages convolutional neural networks to process complex visual data, enabling real-time and high-accuracy defect detection (Ortiz-Cea et al., 2024). This combination of advanced artificial intelligence with the specific context of halal certification represents a pioneering effort to modernize quality assurance in the halal food industry.

The research provides a methodological advancement by developing and validating a CNN model on an extensive dataset collected directly from halal-certified production lines (Sarapure & Kumar, 2024). This ensures that the system is trained on relevant, real-world data, improving its adaptability to practical applications. The focus on metrics such as precision and recall, in addition to accuracy, emphasizes the importance of reliable classification in preventing false negatives that could compromise halal integrity.

The study is justified by the urgent need to ensure consistent quality standards in a rapidly growing global halal food market. By demonstrating the potential of deep learning-driven machine vision, this research supports the development of innovative tools that enhance consumer trust, reduce costs, and strengthen regulatory compliance (Abdullah & Usman, 2022). It contributes to both academic knowledge in artificial intelligence applications and practical solutions for the halal food industry.

RESEARCH METHOD

The research design used in this study applied an experimental quantitative approach combined with computational modeling to develop and evaluate a deep learning-based machine vision system for quality control in halal food production (Hong & Xiao, 2024). The study focused on designing a convolutional neural network (CNN) architecture and testing its ability to classify defects, contamination, and non-halal elements using image datasets collected from halal-certified food processing facilities (Heberling et al., 2012). The design incorporated training, validation, and testing phases to ensure model robustness and reproducibility.

The population in this study consisted of images captured directly from halal food production lines across three categories: raw materials, semi-processed products, and final packaged products. The sample used included 12,500 labeled images, which were divided into 70% for training, 15% for validation, and 15% for testing. The images were selected using stratified sampling to ensure that different types of defects and contamination scenarios were proportionally represented in the dataset (Yu et al., 2022). The diversity of samples was critical for enabling the deep learning model to generalize effectively in real-world industrial applications.

The instruments used in this study included a high-resolution camera system for capturing images under controlled lighting conditions, a computing workstation equipped with GPU acceleration for deep learning computations, and software platforms such as TensorFlow and Keras for model development (Li et al., 2024). Additional image preprocessing was performed using Python-based libraries, including OpenCV, to enhance image quality and prepare the dataset for CNN input (Faieq & Cek, 2024). Evaluation metrics such as accuracy, precision, recall, F1-score, and confusion matrices were employed to assess the performance of the machine vision system.

The procedures began with the acquisition of images from halal-certified production facilities and the manual labeling of data by food quality experts to ensure accurate ground truth (Usman et al., 2020). Data augmentation techniques such as rotation, scaling, and flipping were applied to expand the diversity of the dataset and reduce the risk of overfitting. The CNN model was trained on the augmented dataset using a supervised learning approach, with hyperparameters tuned through validation to achieve optimal performance (Wang et al., 2025). After training, the model was tested on a separate dataset to evaluate its accuracy and reliability in detecting defects and non-halal elements (Zhang et al., 2021). The final stage involved analyzing the confusion matrix and comparing the model's performance with conventional machine vision methods to demonstrate the added value of deep learning in halal food quality control.

RESULTS AND DISCUSSION

The dataset used in this study consisted of 12,500 images collected from halal-certified food production facilities, representing three major categories of products: raw materials, semi-processed products, and packaged products. After preprocessing and augmentation, the dataset was divided into training (70%), validation (15%), and testing (15%) sets. The deep learning model achieved consistent convergence during training, and the performance evaluation results on the test set are presented in Table 1, which includes accuracy, precision, recall, and F1-score for defect detection, contamination identification, and non-halal element classification.

Table 1. Performance Metrics of CNN-Based Machine Vision System

Classification Task	Accuracy (%)	Precision (%)	Recall (%)	F1-score (%)
Defect Detection	96.5	95.2	97.1	96.1
Contamination Identification	97.2	96.0	98.0	97.0
Non-Halal Element Detection	96.8	95.5	97.2	96.3

The explanation of these data shows that the machine vision system powered by deep learning achieved high levels of accuracy across all tasks. The recall values indicate the ability of the model to correctly identify instances of contamination and non-halal elements, which is essential in avoiding false negatives. The F1-scores confirm that the model maintains a balance between precision and recall, providing reliable performance in a production environment.

The descriptive results also demonstrate that the dataset distribution contributed to robust generalization of the model. Data augmentation improved the model's ability to handle variations in lighting, texture, and orientation, which are common in real-world production settings. The misclassification rate was below 4% in all tested scenarios, indicating a high level of consistency.

The inferential analysis involved comparing the CNN-based approach with conventional image processing techniques using paired t-tests. The statistical tests confirmed that the deep learning model significantly outperformed conventional methods in terms of accuracy and recall ($p < 0.01$). The improvement was most pronounced in contamination identification, where the deep learning approach showed a 12% performance gain over traditional methods.

The relationship between dataset diversity and classification performance was also evident. Models trained with a higher proportion of augmented data showed a noticeable reduction in overfitting and improved metrics across all categories. The correlation analysis indicated a strong positive relationship between dataset diversity and F1-score ($r = 0.82$), demonstrating the importance of well-structured data preparation.

The case study conducted on packaged halal food products revealed that the machine vision system could detect packaging defects such as mislabeling, sealing issues, and contamination in real time. During operational testing on a production line, the system achieved a detection speed of 25 frames per second, allowing real-time quality control without slowing down the workflow.

The explanation of the case study findings highlights the operational benefits of integrating deep learning-based vision systems into production environments. The system effectively identified defective or non-compliant products and triggered alerts for corrective action. Human inspectors confirmed that the model reduced inspection errors and increased overall production efficiency.

The interpretation of these results indicates that deep learning-based machine vision provides a reliable and scalable solution for quality control in halal food production. The high performance in classification metrics, coupled with its real-time detection capabilities, shows that this approach can substantially reduce the risk of non-compliance, strengthen consumer trust, and optimize operational efficiency in halal-certified food industries.

The results of this study demonstrate that the application of a convolutional neural network-based machine vision system in halal food production achieves high classification performance and operational efficiency. The system reached an accuracy of more than 96% across defect detection, contamination identification, and non-halal element classification, with corresponding F1-scores above 96%. The recall values were particularly high, showing the system's strength in identifying all critical instances that could compromise product quality and halal compliance. Testing on an operational production line further confirmed the ability of the model to process images at a speed of 25 frames per second, enabling real-time inspection without affecting the production flow.

The findings show that the combination of data augmentation, deep learning algorithms, and structured datasets allows the system to generalize well under variable conditions. Misclassification rates were consistently low and the comparative analysis indicated statistically significant superiority over conventional image processing methods in terms of accuracy, recall, and precision. These results highlight the robustness and reliability of deep learning-driven approaches when applied in complex food production environments.

Comparative discussion with previous studies indicates that the results of this research are consistent with other works that applied deep learning in food inspection but extend the findings into the context of halal food quality control, which has unique and stricter requirements. Studies using traditional machine vision approaches reported moderate success but were limited by low adaptability to variable production conditions such as lighting changes and product diversity. This research confirms that the proposed model overcomes those limitations and performs reliably in dynamic environments. The novelty lies in the model's ability to address halal-specific parameters, including contamination detection that could affect halal compliance, a feature not covered in earlier general food inspection research.

The difference in results from prior studies can also be attributed to the extensive dataset used in this research, which was collected directly from halal-certified facilities and included diverse defect types. While most earlier studies relied on smaller, controlled datasets, this study shows that larger, real-world data substantially improves model robustness. Additionally, this work goes beyond offline evaluation by testing the system on a live production line, an approach rarely reported in earlier literature.

The findings of this research signify an important milestone for the development of intelligent quality control systems tailored to halal food production. These results indicate that deep learning-driven machine vision can be considered a reliable and scalable solution for industries where compliance with religious and quality standards is critical. The ability to automate inspections with high accuracy suggests that halal food producers can integrate artificial intelligence not only to maintain quality standards but also to enhance operational transparency.

The study also highlights that the use of deep learning represents a shift from manual and semi-automated quality inspection methods to a fully automated system that learns from data and continuously improves over time. This marks a broader transition toward Industry 4.0 practices in the halal food sector, positioning the industry to meet future challenges in global supply chain management and traceability.

The implications of these findings are significant for halal-certified producers, regulators, and consumers. Producers can benefit from reduced labor costs and faster inspection cycles while ensuring compliance with halal standards. Regulatory bodies may leverage this technology for traceability and real-time auditing, improving accountability throughout the production process. Consumers, as a result, gain increased confidence in the integrity and safety of halal-certified products, which has become an essential requirement in global markets.

The outcomes of this study also suggest that integrating deep learning models into quality assurance frameworks can support the standardization of halal certification processes. The consistency of machine vision decisions reduces subjectivity, and real-time detection systems can help prevent non-compliant products from reaching the market, thus protecting the halal brand globally.

The high performance of the system can be explained by the structured and diverse dataset combined with advanced neural network architectures. The data augmentation techniques improved the model's capacity to handle variability in real production environments, while the convolutional neural network enabled automated feature extraction without the limitations of manually designed rules. This approach also benefits from iterative optimization and regularization strategies, which enhanced its robustness and minimized overfitting.

The efficiency of the system stems from its ability to analyze visual patterns at a pixel level and learn complex representations that are difficult for conventional models to capture. This capability explains why the system performed significantly better in identifying subtle defects and contamination, even under challenging lighting and orientation conditions, leading to a robust classification performance.

Future work should focus on expanding the scope of machine vision systems for halal compliance monitoring by including multimodal data such as hyperspectral imaging and sensor fusion. These enhancements can enable systems to detect chemical contaminants and other non-visible defects that cannot be identified using standard RGB imagery. Integration with blockchain-based traceability platforms may also provide end-to-end transparency in halal food supply chains.

The next steps should involve pilot deployments of this technology in different halal-certified production environments across regions, combined with cost-benefit analyses to examine scalability and long-term operational impacts. Collaborative efforts between artificial intelligence researchers, halal certification bodies, and industry practitioners will be essential to refine the models and ensure alignment with global halal standards.

CONCLUSION

The most important finding of this research is that the deep learning-based machine vision model demonstrated superior performance in automated quality control for halal food production, achieving an overall accuracy above 96% with a balanced precision and recall across defect detection, contamination identification, and non-halal element classification. The system was able to operate in real time on an active production line at 25 frames per second, significantly reducing human inspection errors and enabling faster and more consistent quality monitoring. These results differ from previous approaches that relied on traditional machine vision techniques, which struggled to maintain reliability under diverse production conditions.

The main contribution of this study lies in introducing a deep learning framework specifically designed for halal food production, integrating convolutional neural networks with an extensive dataset collected from halal-certified facilities. This combination provides a methodological advancement that moves beyond generic food inspection models by focusing on halal-specific quality control challenges. The research contributes not only a scalable and highly accurate technical model but also a conceptual approach that bridges artificial intelligence with halal compliance, offering a replicable framework for industries that require stringent quality standards.

The limitations of this study stem from the use of a dataset collected in a limited number of production environments, which may affect the generalizability of the model to other facilities with different product types and environmental conditions. Future research should focus on building larger and more diverse multimodal datasets, including hyperspectral imaging for non-visible defect detection, as well as deploying and validating the system across multiple halal-certified industries globally. Integration with blockchain-based traceability and real-time feedback systems is also recommended as a direction for expanding the model's application and enhancing transparency in halal food supply chains.

AUTHOR CONTRIBUTIONS

Look this example below:

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest

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