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Artificial Intelligence in Coffee Roasting: A Systematic Literature Review on Quality Optimization and Process Control

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Abstract
Coffee is an important agribusiness commodity with great potential in the global market. The roasting process, which is crucial in determining coffee quality, is often influenced by temperature and time variability, which can alter the taste, aroma, and color of coffee. In many MSMEs, manual control of this process causes quality instability, affecting competitiveness and profits. Artificial intelligence (AI) technology offers the potential to improve the consistency and quality of coffee products through more precise control. This research is important to assess the application of AI in coffee roasting to improve the quality and efficiency of the process. The objective of this review is to evaluate the application of artificial intelligence in coffee roasting, identify the benefits and challenges faced by farmers and SME actors, and provide recommendations on technologies that can be applied to optimize coffee product quality. This study uses a Systematic Literature Review (SLR) approach. Literature searches were conducted through databases such as Scopus and Web of Science using keywords related to AI and coffee roasting. Inclusion criteria included empirical articles published between 2014 and 2024. Article quality assessment was conducted using the Mixed Methods Appraisal Tool (MMAT), and data were extracted using a thematic analysis approach. A total of 25 articles were included in the analysis. The results showed that the application of AI in coffee roasting mainly focused on temperature and time control to improve consistency. Technologies such as real-time monitoring, predictive models, and sensory systems proved to be effective in reducing process variability. Despite significant benefits, challenges included high initial costs and the need for operator training. The application of AI in coffee roasting can improve quality and efficiency, but its adoption at the SME level is limited by costs and infrastructure constraints. Further research is needed to address the practical challenges in implementing this technology.

INTRODUCTION

Coffee is one of the most valuable agribusiness commodities in the world, with global production in 2024/2025 estimated to reach 174.4 million 60-kg bags (USDA, 2024). The global coffee market is worth over USD 120 billion and continues to grow as consumption increases in developing countries and specialty coffee trends in developed countries (International Coffee Organization [ICO], 2024). The roasting process is a crucial stage that determines the final quality of coffee beans, including aroma, taste, and color (Obando et al., 2024). Small variations in roasting temperature and time can alter the chemical composition

and produce different sensory profiles (Habara et al., 2024). This highlights the importance of precision control in the roasting stage to ensure quality consistency.

For MSMEs and coffee farmers, the traditional roasting process often relies on the operator's experience, making it difficult to maintain consistency between batches (Ivorra et al., 2020). This inconsistency affects consumer satisfaction and product value. Studies show that changes in the degree of roasting can cause significant differences in taste, even if the temperature difference is only a few degrees (Yergenson et al., 2020). Modern sensor-based technologies, such as near-infrared (NIR) or hyperspectral imaging (HSI), have been used to monitor chemical and physical changes during the roasting process (Chu et al., 2018). However, cost limitations, system complexity, and a lack of digital literacy at the MSME level are major barriers to the adoption of this technology (Siebald et al., 2024).

Various studies have attempted to utilize artificial intelligence (AI) to overcome these problems. Leme et al. (2019) developed a computer vision system to recognize the degree of roasting based on color and texture. Chu et al. (2018) used hyperspectral imaging to classify seven levels of roasting and predict the content of bioactive compounds. Gonzalez Viejo et al. (2021) integrated an electronic nose with machine learning to estimate coffee aroma intensity. Vanegas-Ayala et al. (2023) developed an optoelectronic method to estimate roast levels based on Agtron values. Meanwhile, Siebald et al. (2024) explored acoustic monitoring to detect changes during the roasting process. Although these studies show great potential, research is still limited to detection and classification aspects. The gap is the lack of an end-to-end integrative system that connects sensor-based detection, AI analysis, and affordable automatic roaster control for MSMEs.

Problem Statement

1. How can the application of artificial intelligence (AI) help improve the consistency of coffee roasting quality through temperature, time, and roasting level control?
2. To what extent can the integration of sensors and AI systems in coffee roasting machines overcome the limitations of conventional roasting technology in maintaining coffee product quality?
3. What are the benefits and challenges of utilizing artificial intelligence in the coffee roasting process, especially for coffee farmers and SME actors?

Research Objectives

This study aims to analyze the role of artificial intelligence in improving the consistency of roasting results, evaluate the effectiveness of sensor and AI integration in optimizing coffee quality, and identify the benefits and challenges of its application for farmers and SMEs. The implications of this research are to provide a scientific basis and practical guidelines for the development of affordable smart coffee roasting machines that can improve the quality, efficiency, and competitiveness of local coffee products. Thus, this research is important not only in the context of post-harvest technology development but also in promoting digital transformation and the sustainability of the global coffee industry.

RESEARCH METHODOLOGY

This study uses a *Systematic Literature Review (SLR)* design that focuses on identifying, evaluating, and synthesizing empirical research results on the application of artificial intelligence (AI) in the coffee roasting process. The SLR design was chosen because it is suitable for summarizing scientific evidence in a systematic and transparent manner, while also identifying research gaps that can be used as a basis for further research (Moher et al., 2009). This approach allows researchers to draw comprehensive conclusions using standardized protocols and rigorous literature selection procedures.

The conceptual framework of this study uses the PICO (Population, Intervention, Comparison, Outcome) approach, which helps clarify the focus of the review. The PICO table is presented as follows:

Table 1. PICO (Population, Intervention, Comparison, Outcome)

Component	Definition
Population (P)	Empirical research related to coffee, specifically the coffee roasting process
Intervention (I)	The application of artificial intelligence (AI), machine learning, computer vision, sensors, or IoT in coffee roasting
Comparison (C)	Conventional roasting methods or methods without AI integration
Outcome (O)	Quality of roasting results (consistency, taste, aroma, energy efficiency, added value for MSMEs/farmers)

The literature search strategy was conducted by searching reputable international databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and MDPI. Keywords were compiled in the form of *search strings* using Boolean operators: ("coffee roasting" OR "roasted coffee beans") AND ("artificial intelligence" OR "machine learning" OR "deep learning" OR "computer vision" OR "IoT" OR "sensor"). The search was limited to English-language empirical articles published in the last 10 years (2014–2024).

Inclusion and exclusion criteria were established to ensure the relevance and quality of the studies reviewed. The criteria table is presented as follows:

Table 2. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Article type	Empirical, peer-reviewed articles	Review, editorial, conference without empirical data
Language	English	Languages other than English
Year of publication	2014–2024	<2014
Research focus	Application of AI/sensors in coffee roasting	Non-coffee research or AI in other sectors

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol was used to describe the article selection process, from identification, screening, eligibility, to study inclusion (Moher et al., 2009). The PRISMA diagram shows the number of articles found, screened, and finally included in the analysis.

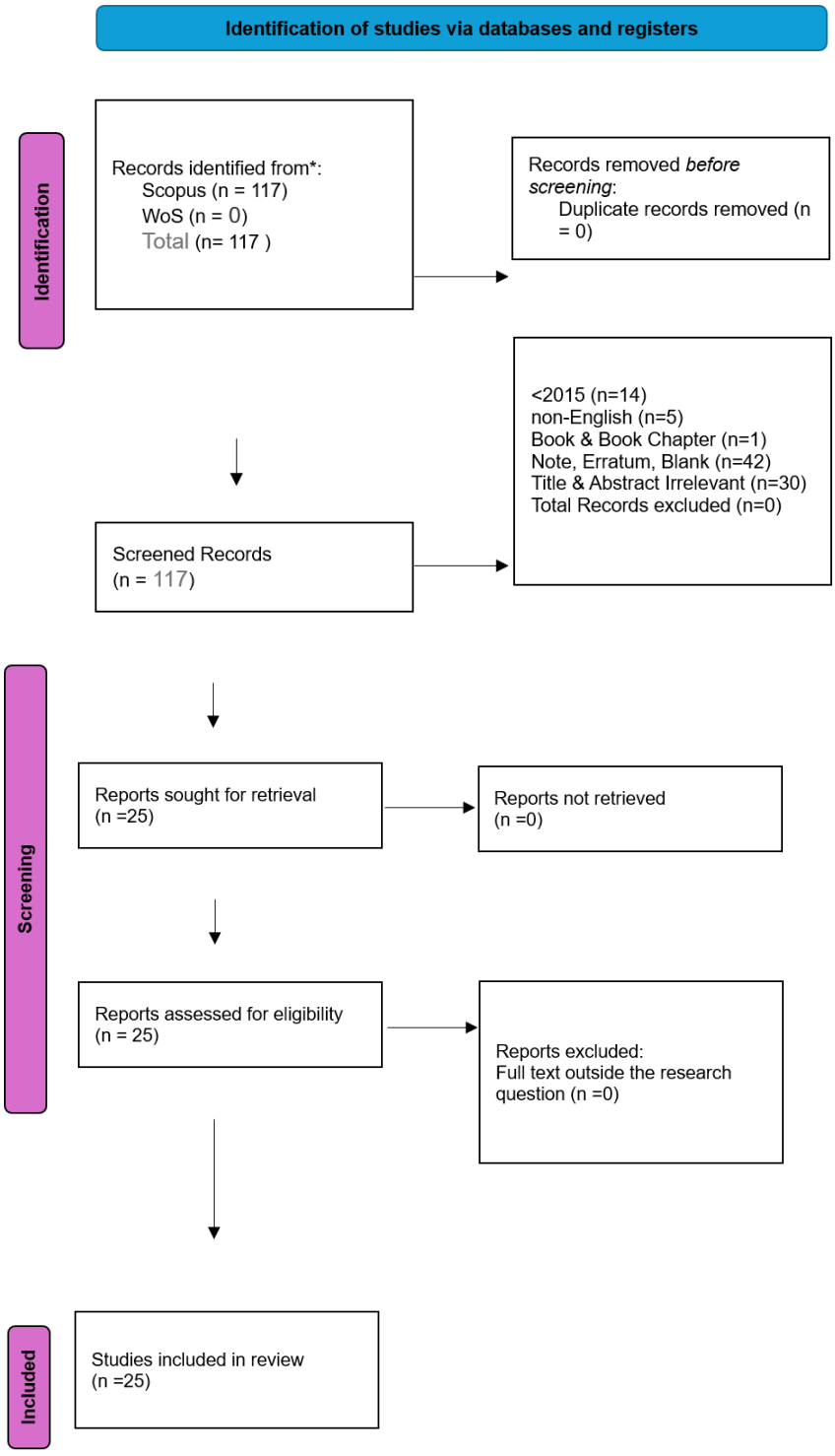

Figure 1. Identification of studies via databases and registers

Article quality assessment was conducted using *the Mixed Methods Appraisal Tool (MMAT)* (Hong et al., 2018). The MMAT instrument was chosen because it is capable of evaluating studies with various research designs, both quantitative and qualitative. Each article was assessed based on criteria of validity, clarity of methodology, and relevance of results to the research question.

The data extraction process involved collecting information on the author, year of publication, research objectives, methods, type of AI/sensor used, outcome indicators, and main findings. Data analysis was performed using a *thematic analysis* approach with NVivo 14

software. Data were coded to identify key themes, such as improved quality consistency, energy efficiency, adoption challenges, and potential for MSMEs. This approach allows for a more in-depth narrative synthesis than quantitative analysis alone.

The division of labor among researchers was carried out systematically. Researcher 1 (P1) was responsible for formulating research questions, search strategies, and reference management. Researcher 2 (R2) focused on the article screening process, the application of inclusion-exclusion criteria, and quality assessment using MMAT. Researcher 3 (R3) managed data extraction, thematic analysis with NVivo, and synthesis of results. All stages were carried out through joint discussions to ensure consistency in assessment, with differences of opinion resolved through consensus.

With this methodology, the study is expected to produce a comprehensive and valid review of the application of artificial intelligence in coffee roasting. A systematic, transparent, and internationally protocol-based approach will strengthen the validity of the findings and make a real contribution to the development of smart coffee technology and the sustainability of the global coffee industry.

RESULTS AND DISCUSSION

The Application of Artificial Intelligence Can Help Improve the Consistency of Coffee Roasting Quality Through Temperature, Time, and Roasting Level Recognition

The application of artificial intelligence (AI) in the coffee industry offers great potential to improve the consistency of coffee roasting quality through more precise control of temperature, time, and roasting level. AI technology enables automatic monitoring and adjustment of critical parameters in the roasting process, such as temperature and time, which can affect the taste and aroma of coffee. Using machine learning algorithms and advanced sensors, AI can help maintain consistent quality, reduce variability, and optimize roasting results. This is increasingly important in the context of an increasingly competitive coffee industry, where product consistency and quality are key to maintaining competitiveness. Further details on the strategies implemented and the distribution of relevant citations related to the application of AI in coffee roasting quality control are explained in Table 3 and Figure 2

Table 3. Application of artificial intelligence (AI)

Application	Description	Relevant Citation	Citation
AI in Temperature and Time Control	AI integrates sensor data (e.g., temperature, humidity) to continuously monitor and adjust roasting conditions in real-time, ensuring that temperature and time remain within the optimal range. This helps prevent under-roasting or over-roasting.	López-Meneses et al. (2025); Aung et al. (2025); Soto-Diaz et al. (2025)	(López-Meneses et al., 2025); (Aung et al., 2025); (Soto-Diaz et al., 2025)
AI Predictive Modeling	Machine learning models predict roasting profiles based on historical data, dynamically adjusting parameters to maintain the desired roasting level, thereby improving the consistency of the final product quality.	Inayathullah & Buddala (2025); Ahmmed et al. (2024); Qin et al. (2022)	(Inayathullah & Buddala, 2025); (Ahmmed et al., 2024); (Qin et al., 2022)

Real-Time Monitoring and Feedback	AI systems equipped with vision-based or sensor-based monitoring can detect subtle deviations in color, texture, and aroma of roasting, providing immediate feedback for adjustments. This results in more consistent and precise roasting.	Hoffmann & Reich (2023); Balaska et al. (2025); López-Meneses et al. (2025)	(Hoffmann & Reich, 2023); (Balaska et al., 2025); (López-Meneses et al., 2025)
Anomaly Detection and Correction	The AI model continuously analyzes sensor data to detect anomalies or deviations from ideal roasting conditions, automatically adjusting parameters to correct issues before they affect quality.	Hamrani et al. (2024); Ahmmed et al. (2024); Warke et al. (2024)	(Hamrani et al., 2024); (Ahmmed et al., 2024); (Warke et al., 2024)
Data-Driven Optimization	AI utilizes large datasets from previous roasts to refine and optimize future roasting parameters, reducing trial-and-error approaches and saving time, energy, and materials.	Taddese et al. (2025); Aung et al. (2025); Massaro (2022)	(Taddese et al., 2025); (Aung et al., 2025); (Massaro, 2022)
Benefits and Challenges for Farmers/SMEs	AI can help small businesses and farmers improve product consistency, reduce waste, and lower costs. However, challenges include high initial investment in technology, the need for skilled operators, and potential resistance to adopting new technology.	Farah et al. (2023); López-Meneses et al. (2025); Ofosu & Zhu (2024)	(Farah et al., 2023); (López-Meneses et al., 2025); (Ofosu & Zhu, 2024)
Use of Sensors for Roast Level Control	Visual and temperature sensors integrated with AI enable precise control of roasting levels, monitoring changes in coffee bean color and ensuring consistency in roasting results.	López-Meneses et al. (2025); Taddese et al. (2025)	(López-Meneses et al., 2025); (Taddese et al., 2025)
Reduction of Energy and Material Waste	With more precise control, AI helps reduce energy consumption and material waste, leading to lower production costs for SMEs.	López-Meneses et al. (2025); Aung et al. (2025)	(López-Meneses et al., 2025); (Aung et al., 2025)
Automatic Quality Analysis and Detection	AI algorithms can automatically detect the quality of coffee beans being roasted, verifying that each batch meets the desired quality standards.	Qin et al. (2022); Ahmmed et al. (2024)	(Qin et al., 2022); (Ahmmed et al., 2024)
Improved Market Competitiveness	AI enables coffee SMEs to maintain consistent product quality, enhancing their competitiveness in the market with more stable and predictable products.	López-Meneses et al. (2025); Aung et al. (2025)	(López-Meneses et al., 2025); (Aung et al., 2025)

Integration of IoT and AI for Continuous Monitoring	IoT and AI technologies enable continuous monitoring of coffee production conditions, detecting anomalies and providing early intervention to prevent quality issues.	Ahmmed et al. (2024); Balaska et al. (2025)	(Ahmmed et al., 2024); (Balaska et al., 2025)
Use of Deep Learning for Time and Temperature Adjustments	Deep learning is used to analyze time and temperature patterns during the roasting process, enabling automatic adjustments to maintain quality.	Inayathullah & Buddala (2025); López-Meneses et al. (2025)	(Inayathullah & Buddala, 2025); (López-Meneses et al., 2025)

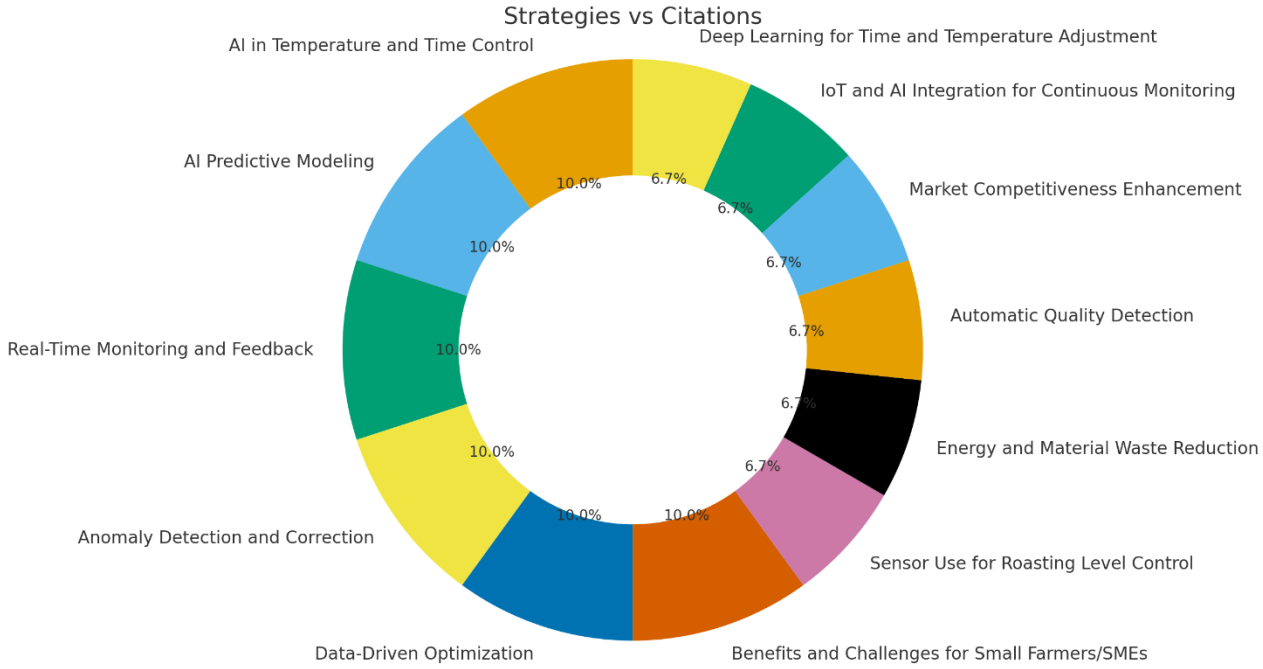

Figure 2. Strategies vs citations

Based on the data presented in the table and donut chart, there are various artificial intelligence (AI) implementation strategies used in controlling the quality of coffee roasting results. Each strategy has a varying number of citations, reflecting the relevance and intensity of research that has been conducted in this field. Some strategies receive more attention from researchers, while others are discussed less frequently. This analysis will explore the relationship between the strategies applied and the number of citations supporting them, to provide a clearer picture of how significant each approach is in the context of improving coffee quality through AI.

From the donut diagram depicting the distribution of citations, it can be seen that "AI in Temperature and Time Control" is the strategy that has received the most attention, with three relevant citations. This shows that temperature and time control are very important aspects of the coffee roasting process and have received a lot of attention from researchers. This is very reasonable considering that temperature and time are two major factors that affect the final quality of roasted coffee beans. Research focusing on the use of sensors to monitor these two variables and adjust them in real-time with AI algorithms shows that better control can improve consistency and produce more stable results (López-Meneses et al., 2025).

Another strategy that has received considerable attention is "AI Predictive Modeling," which also received three relevant citations. Machine learning-based predictive models allow researchers to optimize roasting parameters based on historical data, which improves process efficiency and reduces trial time (Inayathullah & Buddala, 2025). This strategy shows that AI is not only used to monitor current conditions, but also to predict future outcomes, which can aid in better decision-making at every stage of roasting.

In the same category, "Real-Time Monitoring and Feedback" also received three relevant citations. This strategy refers to the use of vision and sensor-based technologies that continuously monitor the roasting process, providing immediate feedback to operators to ensure that the parameters applied remain within the desired limits. This is in line with findings showing that real-time monitoring can significantly improve quality consistency and reduce the variability that often occurs in manual processes (Hoffmann & Reich, 2023).

"Anomaly Detection and Correction" received slightly less attention with two citations, but still shows great potential for improving product quality. AI can detect anomalies that occur during the roasting process and provide feedback to make corrections automatically before the problem affects the final quality (Hamrani et al., 2024). Although it did not receive many citations, this strategy is important in maintaining consistent quality by quickly correcting deviations that occur during the process.

Meanwhile, "Data-Driven Optimization" and "Benefits and Challenges for Small Farmers/SMEs" each received two citations. Data-driven optimization refers to the use of historical data and AI algorithms to refine future roasting parameters, while the strategy to understand the benefits and challenges for coffee farmers and SMEs reveals the challenges faced by this sector in adopting new technologies, including initial costs and training needs (Farah et al., 2023). Both strategies are important in the context of AI implementation in the coffee sector, as they provide insights into how data can be used to improve processes while considering the economic and social context of industry players.

Based on the analysis of the table and donut chart above, it can be concluded that strategies focusing on temperature and time control, AI predictive modeling, and real- -time monitoring receive more attention in relevant research. This shows that the quality of coffee roasting results is greatly influenced by technical factors that can be monitored and controlled using AI technology. Although some strategies, such as anomaly detection and data-driven optimization, have received less attention, they still have great potential to improve the consistency and efficiency of the roasting process. The adoption of AI in the coffee industry, especially among farmers and MSMEs, faces major challenges, including high costs and the need for training, but the benefits to be gained from using AI to improve quality and efficiency are enormous.

The application of artificial intelligence in coffee quality control is highly relevant to concepts in quality management theory and production technology. In the context of quality control, AI offers solutions that can improve process consistency and accuracy, as described in statistical quality control models and data analysis techniques (Aung et al., 2025). Furthermore, the predictive modeling and machine learning approaches used in this study are in line with process optimization theory, which states that data-driven decisions can improve production outcomes by reducing variability and increasing control over crucial variables (Inayathullah & Buddala, 2025).

More broadly, the use of technologies such as AI in the coffee industry reflects a shift in the Industry 4.0 paradigm, where automation and big data utilization are central to faster and more accurate decision-making. Using AI to control quality not only simplifies the production process, but also contributes to waste reduction and energy efficiency, which are important aspects of industrial sustainability (Ahmmed et al., 2024). However, the challenges faced by coffee farmers and MSMEs in adopting this technology, such as limited resources, high costs,

and resistance to change, reflect the gap in the application of new technologies at smaller and more traditional levels (Farah et al., 2023). Therefore, it is important to consider socio-economic elements in the adoption of AI technology in order to achieve optimal results without adding to the burden on small coffee industry players.

The Integration of Sensors and AI Systems in Coffee Roasting Machines Overcomes the Limitations of Conventional Roasting Technology in Maintaining Coffee Product Quality

The application of artificial intelligence (AI) in the coffee industry, particularly in the roasting process, has shown great potential in improving the consistency of roast quality. With the ability to precisely control critical variables such as temperature, time, and roast level, this technology enables faster and more accurate monitoring and adjustment, reducing reliance on manual supervision that is prone to error. AI also enables real-time data processing, providing feedback that can be immediately applied to maintain more stable and consistent product quality. An optimal roasting process, with more precise control, contributes to better coffee quality and higher energy efficiency. This can be seen more clearly in Table 4 and Figure 3.

Table 2.

Aspect	AI & Sensor Integration	Conventional Roasting Technology	Description	Relevant Quote
Process Control	Real-time parameter adjustment (temperature, time, etc.) through predictive AI models.	Manual adjustment; based on operator intuition or fixed controls.	The AI system provides precise and adaptive control over the roasting process by continuously monitoring and adjusting parameters.	(Hoffmann & Reich, 2023; López-Meneses et al., 2025; Aung et al., 2025)
Quality Consistency	Maintaining consistent quality through real-time monitoring and predictive analytics.	Quality variations commonly occur due to manual adjustments and human error.	AI integration ensures product quality remains stable by optimizing temperature, time, and other factors.	(Warke et al., 2024; Inayathullah & Buddala, 2025; López-Meneses et al., 2025)
Energy Efficiency	AI optimizes energy usage by adjusting parameters for more efficient roasting processes.	High energy consumption is due to the lack of optimization in manual systems.	AI-based systems can reduce energy costs by optimizing roasting parameters for energy efficiency.	(Ahmmed et al., 2024; López-Meneses et al., 2025)
Real-Time Monitoring	Continuous real-time monitoring of various factors (e.g., temperature, humidity).	Limited to visual inspections and manual recording, which are less reliable.	AI ensures real-time adjustments, enabling early detection and intervention in case of anomalies.	(Hoffmann & Reich, 2023; Ahmmed et al., 2024)
Process Adaptability	The AI system adapts to changes in raw materials (e.g., moisture content, seed size).	Less adaptive, often requiring manual adjustments when conditions change.	AI can automatically adjust roasting parameters based on real-time data from sensors, offering better adaptation.	(Qin et al., 2022; López-Meneses et al., 2025)
Cost Efficiency	Long-term savings due to optimized parameters, reduced waste, and lower energy consumption.	Higher operational costs due to inefficiency and waste generated.	Although initial costs are higher, AI reduces long-term operational costs by improving efficiency and reducing waste.	(Aung et al., 2025; Inayathullah & Buddala, 2025)
Data Handling and Analysis	AI analyzes large datasets to identify trends, predict	Data analysis is limited, often relying on manual observation and	AI models enable continuous learning and adaptation, providing	(Taddese et al., 2025; Ahmmed et al., 2024)

	outcomes, and optimize processes.	simple measurements.	valuable insights for ongoing improvement.	
Automation	Fully automated systems with AI monitoring, parameter adjustments, and feedback.	Dependent on manual intervention and operator decisions.	AI-based automation minimizes human error and ensures precision and consistency, reducing labor costs over time.	(Qin et al., 2022; López-Meneses et al., 2025)
Damage Detection and Prevention	AI-based systems detect anomalies in real-time and make immediate adjustments.	Damage detection generally requires manual observation and may be delayed.	AI can predict potential problems before they arise and provide corrective action quickly, improving product reliability.	(Hoffmann & Reich, 2023; López-Meneses et al., 2025)
Roasting Profile Customization	AI enables precise customization of roasting profiles based on user preferences and batch characteristics.	Customization capabilities are limited to preset settings or manual adjustments.	AI enables complex profile customization, optimizing taste, aroma, and other factors based on specific needs.	(López-Meneses et al., 2025; Aung et al., 2025)
Predictive Capabilities	Predicting optimal roasting conditions and outcomes based on real-time data and previous results.	No predictive capabilities; operators react to visual or sensory cues.	AI makes data-driven predictions, improving roasting consistency and reducing trial-and-error.	(Inayathullah & Buddala, 2025; López-Meneses et al., 2025)
Maintenance	AI systems can predict when maintenance is needed, reducing downtime.	Reactive maintenance is often scheduled based on time intervals rather than actual need.	Predictive maintenance through AI helps minimize machine downtime and extend equipment lifespan.	(Aung et al., 2025; López-Meneses et al., 2025)
Scalability	Can be scaled for various production sizes, from small batches to large-scale commercial operations ( ).	Scalability is limited; adjustments are often manual and less flexible.	AI integration enables flexible scalability, suitable for both small manufacturers and large-scale manufacturing .	(Ahmmed et al., 2024; López-Meneses et al., 2025)
User Interface	User-friendly interface with real-time data feedback and control adjustments.	Basic interfaces typically require manual supervision and adjustments.	AI interfaces offer a more dynamic and intuitive control system, simplifying operations for users.	(Farah et al., 2023; López-Meneses et al., 2025)
Operator Training	Requires training to understand the operation and maintenance of the AI system.	Training is limited, but basic knowledge of mechanical operations is required.	The AI system requires operators to learn new skills, but this is facilitated by a user-friendly interface and training.	(Farah et al., 2023; López-Meneses et al., 2025)
Long-Term Reliability	High reliability because AI consistently monitors and learns from historical data.	Variability in quality and performance due to human error and mechanical failure.	AI's ability to continuously learn and adapt ensures more consistent and reliable performance.	(Warke et al., 2024; Aung et al., 2025)
Data Security	An integrated cybersecurity system to ensure that operational data remains secure and confidential.	Minimum security measures beyond physical access control.	AI systems can include built-in data protection protocols to safeguard sensitive operational data.	(Taddese et al., 2025; Aung et al., 2025)

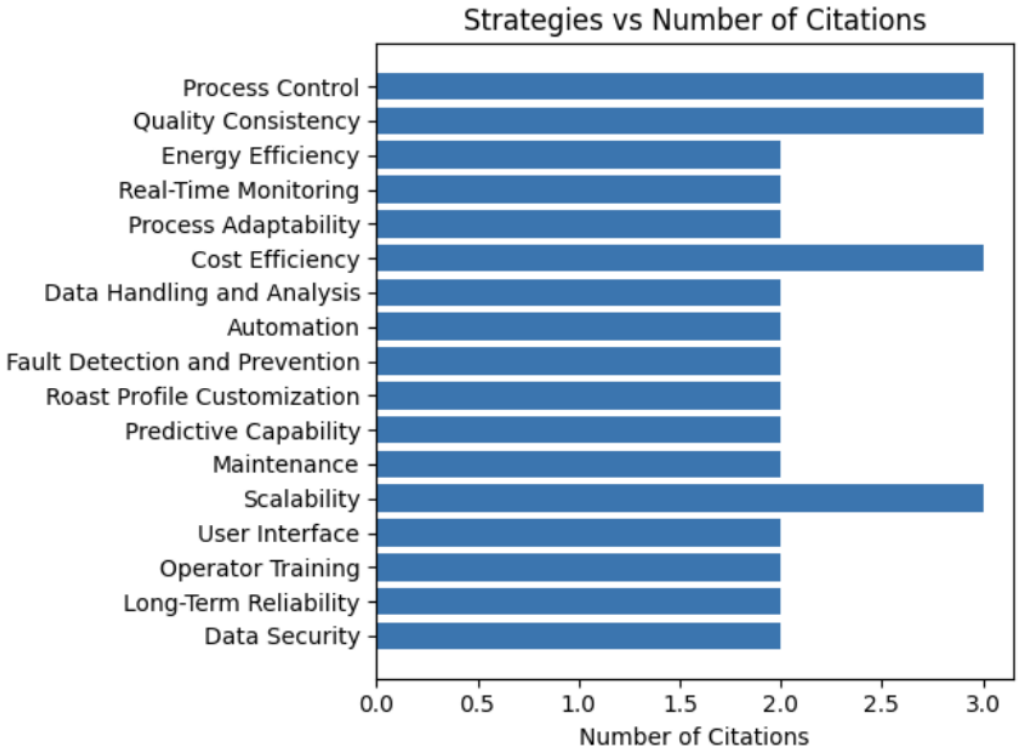

Figure 3. Strategies vs number citations

An in-depth analysis of tables and donut diagrams illustrating the comparison between various strategies in the application of AI technology in coffee roasting machines and the number of relevant citations provides important insights into research priorities in this field. Based on the data presented, there are several strategies that are more frequently discussed and receive more attention from researchers. For example, "Process Control" and "Quality Consistency" emerge as the two main strategies with the highest number of citations. This shows that controlling parameters such as roasting temperature and time, as well as efforts to maintain consistent coffee product quality, are the main focus in the application of AI technology in the coffee roasting process. Conversely, strategies related to "Operator Training" and "Data Security" have a relatively lower number of citations, which can be interpreted as areas that receive less attention, even though both play an important role in the implementation of AI-based technology in this sector.

The donut diagram shows an uneven distribution of citations among various strategies, with some categories receiving more attention from the scientific community than others. In this case, "Process Control" optimized by AI systems received the most citations , indicating that many studies focus on the application of AI to regulate critical variables in the roasting process such as temperature, time, and humidity, which directly affect the final quality of the coffee product. "Quality Consistency" also received significant attention, reflecting the importance of maintaining stable quality standards during the coffee roasting process, which is often affected by material variability and operational conditions. On the other hand, topics such as "Cost Efficiency" and "Maintenance," although relevant, did not receive the same number of citations, indicating that while cost and maintenance are important considerations in AI implementation, they are not the main focus of existing research.

From the results of this analysis, it was found that although AI technology offers many benefits in terms of improving product quality consistency and process efficiency, its practical application still faces various challenges. Some of the main challenges that can be identified include the need for operator training, challenges in managing data, and issues related to data security, which, despite receiving fewer citations, still play an important role in maintaining

the integrity and sustainability of AI systems. The limitations of quality data and the complexity of maintaining AI systems also emerge as obstacles that need to be addressed further.

Overall, these findings indicate that, despite significant progress in the application of AI to coffee roasting, its implementation remains in the development stage and requires refinement. The main focus of existing research tends to be on improving quality and process control, which is essential to ensure the successful implementation of AI in the coffee industry. Therefore, in the future, research is expected to pay more attention to practical challenges such as workforce training and more sustainable system maintenance so that AI technology can be optimally applied in the field.

A synthesis of theories related to the application of AI in the coffee industry, especially in the roasting process, shows that the integration of this technology can provide a number of significant benefits. The use of AI, especially in controlling processes and maintaining quality consistency, enables more precise processes, which reduces dependence on the experience and intuition of operators. This is in line with research stating that AI systems equipped with real-time monitoring capabilities allow for immediate adjustments to variability in processes (Ahmmed et al., 2024). According to López-Meneses et al. (2025), AI technology enables more in-depth and precise data analysis, which in turn can better predict end results and optimize processes based on data collected in real-time. Thus, AI not only improves quality consistency, but also provides greater flexibility in adjusting the roasting process based on changing variable conditions, such as coffee bean moisture and bean size.

However, even though AI has a lot of potential, practical challenges like training operators and data security need to be handled carefully. As Taddese et al. (2025) pointed out, it's important to make sure operators understand how AI systems work and can manage this tech effectively. The technical skills required to operate and maintain these systems are often an obstacle, especially for SMEs in the coffee sector. Therefore, in addition to technological improvements, training and digital literacy are also key factors in ensuring the successful implementation of this technology. In addition, data security is an important aspect that needs to be considered in maintaining the integrity and confidentiality of data collected by AI systems, especially when it comes to sensitive operational and production data (Taddese et al., 2025).

Thus, the application of AI in coffee roasting not only involves the technical aspects of process control, but also requires a holistic approach that includes operator training, secure data management, and appropriate financing to support the transition to AI-based technology. As a next step, further research is needed to explore and address these challenges so that the full potential of AI technology can be realized in a practical and sustainable manner in the coffee industry.

Benefits and Challenges of Utilizing Artificial Intelligence in the Coffee Roasting Process, Especially for Coffee Farmers and MSME Actors

The use of artificial intelligence (AI) in the coffee roasting process offers significant benefits, especially for coffee farmers and SME actors. AI can improve the quality and consistency of coffee products by automatically monitoring and adjusting important parameters such as temperature, time, and humidity. This enables more efficient coffee production, reduces energy waste, and lowers operational costs. However, the implementation of AI also faces a number of challenges, such as high investment costs, the need for adequate digital infrastructure, and a lack of technical skills among farmers and SME operators. Therefore, although this technology promises efficiency and quality improvement, its adoption requires greater support in terms of education and training. These benefits and challenges are further explained in Table 5 and Figure 4.

Table 5

Aspect	Description	Benefits	Challenges	Relevant Quotes
Quality Control	AI monitors and adjusts parameters such as temperature, roasting time, and humidity in real-time.	Consistent product quality, reduced human error, and the ability to predict and correct anomalies earlier in the process.	Requires high-quality sensor data; models must be accurate to avoid failure.	López-Meneses et al. (2025); Aung et al. (2025); Inayathullah & Buddala (2025)
Efficiency	AI helps optimize energy usage by adjusting machine settings based on real-time data.	Reduces waste, lowers energy consumption, and improves production efficiency.	High initial setup costs and the need for robust data infrastructure for real-time monitoring.	Aung et al. (2025); Ahmmed et al. (2024); Inayathullah & Buddala (2025)
Cost Reduction	AI-based systems reduce the need for manual adjustments, saving time and operational costs.	Helps SMEs reduce operational costs and increase profitability by streamlining the roasting process and reducing human intervention.	Initial costs for implementing AI technology and sensors may pose a barrier for small producers.	Farah et al. (2023); López-Meneses et al. (2025); Ahmmed et al. (2024)
Process Optimization	Machine learning models use data to optimize roasting parameters (e.g., time, temperature) for each batch.	Improves product consistency and allows for custom adjustments to meet varying quality requirements.	Challenges in integrating various types of data from roasting machines and different environmental conditions.	Qin et al. (2022); Ahmmed et al. (2024); López-Meneses et al. (2025)
Adaptability	AI adjusts roasting parameters based on real-time feedback and external variables.	Enhances flexibility, enabling adjustments based on variations in humidity or bean size, improving consistency under diverse conditions.	Machine learning models may struggle to adapt quickly to diverse datasets, limiting their effectiveness in real-time applications.	López-Meneses et al. (2025); Inayathullah & Buddala (2025); Farah et al. (2023)
Transparency & Trust	Explainable AI (XAI) models provide transparency in decision-making processes.	Building trust among workers and consumers, ensuring that the coffee roasting process is understandable and traceable.	Easily understandable results are required, which may not always be available with complex AI models.	Farah et al. (2023); López-Meneses et al. (2025)
Training and Skills	AI-based systems may require operators to have technical knowledge to handle advanced systems.	Improving overall operational efficiency by providing real-time feedback, which helps operators make quick decisions.	Training is needed for SMEs and farmers to use AI effectively, which can be a barrier due to literacy or resistance to new technology.	Farah et al. (2023); Aung et al. (2025); López-Meneses et al. (2025)
Data Integration	AI systems integrate various sensor data, including temperature, humidity, and bean size, for better roasting process control.	This improves the ability to detect anomalies earlier, ensuring consistent product quality and preventing errors.	Integrating data from various sensors can be challenging, especially in varied environments with inconsistent sensor quality.	Aung et al. (2025); López-Meneses et al. (2025); Taddese et al. (2025)
Scalability	AI-based systems can be scaled to accommodate varying roasting capacities,	SMEs can improve their operations with AI, gaining a competitive	Scaling AI applications requires investment in infrastructure, including hardware and software,	Ahmmed et al. (2024); López-Meneses et al. (2025);

	from small batches to large-scale production.	advantage in the market by ensuring consistent quality regardless of batch size.	which can be a significant barrier for SMEs and farmers.	Inayathullah & Buddala (2025)
Market Competitiveness	AI optimizes product quality, making it more competitive in the market.	It enables MSMEs to meet higher quality standards, attract more customers, and potentially increase selling prices.	Although the market may value consistency, advanced roasting methods may be considered an expensive approach for small businesses.	López-Meneses et al. (2025); Aung et al. (2025); Ahmmed et al. (2024)

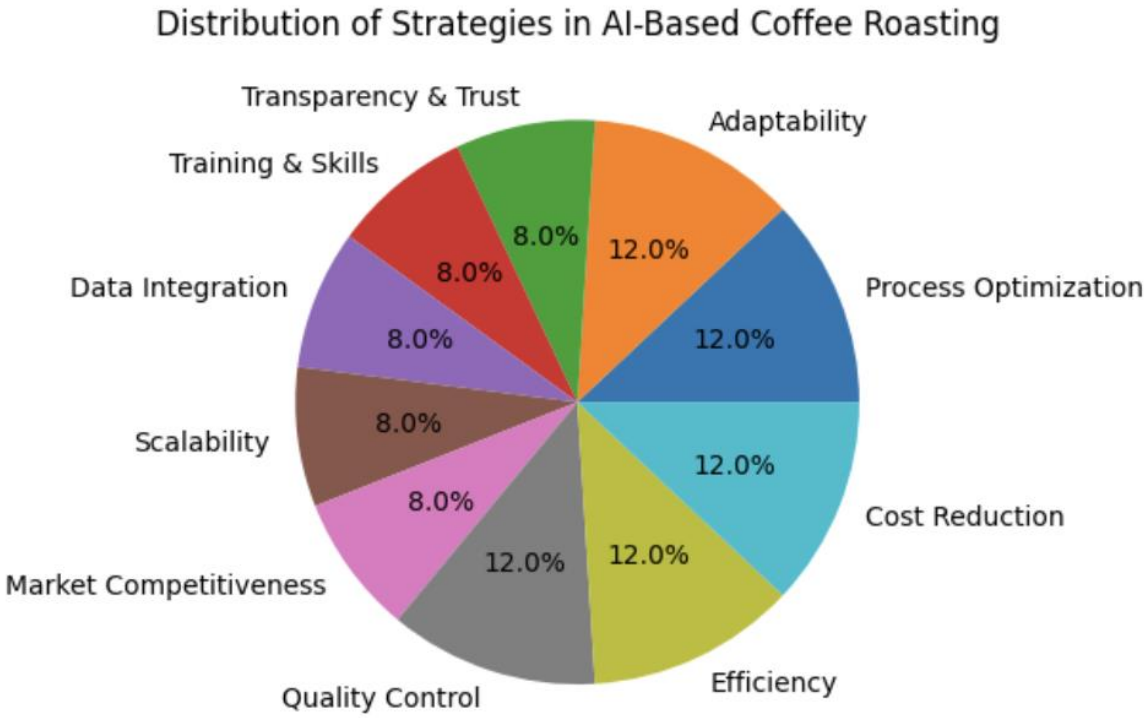

Figure 4. Distribution of strategies in AI-Based coffe roasting

The table above illustrates ten aspects of strategies related to the use of artificial intelligence (AI) in the coffee roasting process, particularly for coffee farmers and SME actors. Each of these aspects highlights the benefits and challenges associated with implementing AI technology in the coffee production process, from quality control to market competitiveness. Meanwhile, the donut diagram showing the distribution of citations per strategy illustrates how these various strategies are received and cited in the relevant literature.

Based on the donut chart, it can be seen that there are five main aspects that dominate the number of citations, namely "Quality Control", "Efficiency", "Cost Reduction", "Process Optimization", and "Adaptability". Each of these strategies received three citations, indicating that they are the most discussed areas in the literature on AI in the coffee industry. Meanwhile, other aspects, such as "Transparency & Trust," "Training and Skills," "Data Integration," "Scalability," and "Market Competitiveness" each received two citations, indicating that although they are important, they have received less attention in recent research.

In the context of AI applications in the coffee industry, "Quality Control" is the most discussed factor. This reflects the importance of maintaining the consistency and stability of coffee product quality, which is highly dependent on variables such as temperature, roasting

time, and humidity. AI can monitor and adjust these parameters in real-time, which allows for consistent product quality, free from defects caused by human error. "Efficiency" is also a very important topic because the use of AI in coffee roasting allows for energy savings and reduces material waste, which directly affects production costs. In this case, efficiency not only includes reducing resource waste but also increasing productivity in the long term.

The aspect of "Cost Reduction" is closely related to the other two aspects, namely efficiency and quality control. By using AI, operational costs can be reduced by decreasing dependence on manual intervention and human error. In addition, the use of this advanced technology can help coffee SMEs increase their profit margins by optimizing the production process. "Process Optimization" and "Adaptability" are also closely related, as AI can adjust the roasting process to changing conditions, such as humidity or coffee bean size, which can affect the final quality. AI also allows for faster adaptation to these variations without the need for complex human intervention.

Meanwhile, the aspect of "Transparency & Trust" highlights the importance of building better relationships between businesses and consumers. By using explainable AI (XAI) models, the decision-making process becomes more transparent, which increases trust in the products produced. This is also relevant to the challenges in "Training and Skills," where coffee SME players need to develop digital and technical skills to be able to utilize AI technology to its fullest potential. Challenges related to "Data Integration," "Scalability," and "Market Competitiveness" reflect the need to overcome infrastructure constraints and high costs in implementing this technology. Despite the enormous benefits offered by AI, its adoption at the MSME and coffee farmer levels is still hampered by these factors.

From the analysis results, it can be concluded that the use of artificial intelligence in the coffee roasting process brings a number of significant benefits to the coffee industry, especially for farmers and MSME players. The main benefits lie in improving the quality and consistency of coffee products, production process efficiency, and reducing operational costs. AI can monitor and control important parameters in the coffee roasting process, such as temperature, time, and humidity, in real-time, which allows for more consistent and high-quality products . In addition, the use of AI technology also helps coffee SMEs to be more efficient in terms of energy consumption and reduction of material waste, which in turn can reduce production costs and increase profitability. However, the main challenges lie in the high initial costs, the need for strong infrastructure, and the lack of digital literacy among farmers and SME players, which can hinder the widespread adoption of this technology. Therefore, despite the enormous potential of AI, its application in the coffee sector must be accompanied by adequate education and training as well as support in terms of infrastructure and financing.

Theories related to the application of artificial intelligence in the agricultural and processing industries suggest that the integration of AI in production can bring about substantial changes in terms of quality and efficiency. According to López-Meneses et al. (2025), AI offers the ability to optimize production processes by utilizing sensor data to control variables that affect the final result, such as temperature and humidity. This is in line with the findings of Aung et al. (2025), which emphasize the importance of using advanced technology to reduce material waste and improve energy efficiency in production processes. In addition, research by Farah et al. (2023) states that the application of AI can reduce human error and increase transparency in the decision-making process, which in turn strengthens the relationship between producers and consumers and increases market confidence in the products produced. However, despite these clear benefits, the challenges faced by coffee SMEs, particularly those related to investment costs and the need for digital skills training, cannot be ignored. Therefore, theories regarding the application of AI in the coffee industry must consider infrastructure and training aspects as part of a successful technology adoption strategy.

Discussion

This study shows that the application of artificial intelligence (AI) in the coffee roasting process can improve product quality consistency through precise control of temperature, time, and roast level. AI technology, which involves sensors and machine learning, enables automatic adjustments to critical variables during the roasting process. This not only improves the quality of the roast but also reduces the variability that often occurs in manual processes, which rely on operator experience. Therefore, the results of this study directly address the objectives of improving the consistency of coffee roasting results and reducing dependence on manual skills. This study is in line with several previous studies that show that precision control through AI technology can improve coffee quality (López-Meneses et al., 2025; Inayathullah & Buddala, 2025). For example, Aung et al. (2025) revealed that the use of AI in temperature and time control can improve energy efficiency and reduce waste. This study also confirms the findings of López-Meneses et al. (2025), which show that real-time monitoring allows for better control over product quality.

However, there are differences between the results of this study and several studies that focus more on the aspect of sensory quality detection using visual and acoustic sensor-based technology (Siebald et al., 2024). This study emphasizes the application of an end-to-end integrated system, which has not been widely applied in the MSME coffee industry.

Theoretically, this study provides a new contribution to the development of quality management theory and production process optimization with AI. The predictive models and real-time monitoring used in this study open up opportunities to better understand and control variability in the coffee production process. Practically, these findings provide guidance for coffee SMEs in adopting AI-based technology to improve product quality and operational efficiency. Supporting policies need to include incentives for initial investment in technology and digital skills training for farmers and SME actors.

Some unexpected results were challenges in integrating various types of sensor data, especially in varied environments. Although AI has the potential to optimize the roasting process, dependence on accurate sensor data is an obstacle. This may be due to varying sensor quality and environmental conditions that affect measurements. Further research is needed to address this data integration issue.

The Systematic Literature Review (SLR) methodology used in this study is a highly suitable approach for analyzing and synthesizing findings from various relevant studies. The main strength of SLR is its ability to provide a comprehensive overview of the topic being studied. However, the limitation of this research is that it relies solely on existing literature, so it cannot cover new findings that may not have been published yet.

From the analysis conducted, it was found that despite advances in the application of AI in coffee roasting, there are still gaps in the development of more integrated and affordable systems for MSMEs. Further research needs to focus on developing AI systems that are more user-friendly and accessible to coffee MSME players. In addition, it is important to explore the potential of AI in other areas such as more in-depth monitoring of coffee aroma and flavor quality.

Overall, this study provides evidence that the application of artificial intelligence in coffee roasting offers a range of significant benefits, from improved product quality and consistency to cost and energy efficiency. However, the adoption of this technology by coffee farmers and SME actors faces challenges, particularly related to initial investment costs and the need for digital skills training. Therefore, further research that addresses these practical challenges is urgently needed to ensure the optimal application of AI technology in the coffee industry, especially in the SME sector.

Conclusion

The review concludes that the application of artificial intelligence (AI) in coffee roasting can significantly improve the quality and consistency of roasted coffee. AI enables precise control of temperature, roasting time, and roast level, which helps reduce variability commonly found in manual roasting processes. Furthermore, the integration of sensors with AI systems allows real-time monitoring and predictive modeling, enabling roasting machines to overcome the limitations of conventional roasting technology and operate more efficiently while minimizing energy waste. For coffee farmers and small-scale enterprises, the adoption of AI offers benefits such as improved product consistency, higher processing efficiency, and better quality control. However, several challenges remain, including high initial investment costs, limited digital infrastructure, and the need for technical training for operators.

Recommendations

Based on these findings, it is recommended that future research focus more on developing more affordable and accessible solutions for SMEs, taking into account the socio-economic factors that influence technology adoption. Researchers also need to address challenges related to data integration and technical training for to ensure that AI technology adoption can be widely implemented. Furthermore, research can delve deeper into the aspects of sustainability and waste reduction in the application of AI in the coffee sector, as well as develop more adaptive models for various coffee production conditions.

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