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Review of artificial intelligence powered food processing: enhancing safety and sustainability

Deribe Mengistu^{1*}, Girma Ashe²

¹ *Food Science and Nutrition, Food Engineering, Deber Zeit Agricultural Research Centre, Bishoftu, Ethiopia.*

² *Agricultural breeding, Breeder, Deber Zeit Agricultural Research Centre, Bishoftu, Ethiopia*

**Corresponding author: deribem462@gmail.com*

Abstract

As the global population is projected to reach 9.7 billion by 2050, ensuring food security has become increasingly challenging due to factors such as population growth, climate change, resource depletion, and environmental pollution. To address these challenges, artificial intelligence (AI) is an emerging technology that plays a crucial role in the food processing industry. This review highlights AI's essential role in food processing to enhancing the quality and safety of food products sustainably while addressing industry challenges. Artificial Intelligence significantly impacts food safety, quality assurance, and waste reduction through various applications. Its integration into food processing has the potential to revolutionize industry standards, covering tasks from product categorization to personalized nutrition. However, challenges such as job displacement, technical limitations, and ethical considerations require careful attention. Investment in research, development, training, and maintenance is crucial for successful AI integration. Despite these hurdles, AI's transformative potential to advance sustainability, food safety, and consumer needs remains significant. Artificial Intelligence is poised to enhance efficiency, foster innovation, and improve sustainability in the food processing sector, effectively addressing the evolving needs of the growing global population. Artificial Intelligence promotes a hopeful outlook for the future of food processing, confidently tackling 21st-century challenges with adaptability and resourcefulness. **Keywords:** Artificial intelligence, food processing optimization, sustainability, AI-driven food safety.

1. Introduction

The population of the world has grown to 8 billion and is expected to reach 9.7 billion by 2050, which has resulted in a greater demand for food production [1]. Ensuring food security is a top priority for all nations worldwide. However, the complex interaction of factors such as population growth, climate change, resource depletion, and environmental pollution continues to strain food systems [2]. Artificial Intelligence plays a crucial role in food processing, emphasizing security and quality management. It employs image processing, robotics, and AI-driven fertilizer management

to guarantee food safety. Additionally, it also enhances product quality, production efficiency, and pesticide management, benefiting both crops and consumers [3]. AI-enabled technologies offer numerous benefits in agriculture and the food industry. They can predict weather conditions, analyze crop sustainability, identify pesticides in fields, recognize defective raw materials during sorting, and monitor workers' activities in production areas. The use of artificial intelligence in these sectors significantly impacts gross domestic product [4]. Food quality and safety are significant concerns for society as they form the foundation

of human health, social development, and stability. Guaranteeing food quality and safety is a multifaceted process that encompasses all stages of food processing, from cultivation, harvesting, and storage to preparation and consumption. Although these processes can be labor-intensive, the advancement of machine vision technology can greatly benefit researchers and industries by enhancing the efficiency of food processing [5]. In the food processing industry, prioritizing the quality and safety of food is paramount. Effective packaging technology serves as a linchpin in preserving the freshness and integrity of food items for consumers. Consequently, innovations in food packaging are indispensable for meeting the escalating global demand for elevated standards of food quality and safety [6]. Artificial intelligence, a branch of science that utilizes intelligent machines to perform tasks requiring human intelligence, can significantly enhance sustainable food security. It can optimize production patterns, transportation, supply chain management, marketing, and various food-related applications [7]. Artificial intelligence integrated into the agri-food sector has the power to reshape the industry by empowering farmers, food producers, and distributors with advanced decision-making capabilities. This technology enhances operational efficiency, minimizes waste, and fosters greater food security and sustainability [8]. The current agricultural and supply chain frameworks significantly contribute to these challenges. With the expansion of the global population, the need to incorporate technology into food production processes has become more urgent. Artificial intelligence has emerged as a promising solution, providing opportunities to increase agricultural output and alleviate poverty through its application in farming. By utilizing AI, we can improve food production efficiency and meet the increasing demands of our growing population, thus advancing global food security [9].

Artificial intelligence in food processing involves the utilization of algorithms and computational models to enhance efficiency, quality, and safety in various aspects of the food industry. Artificial intelligence applications in food processing include sorting products, monitoring food quality, optimizing supply chains, and ensuring food safety compliance

[10,11]. By implementing AI techniques, the food industry can improve productivity, reduce waste, and enhance customer experience through personalized nutrition and efficient inventory management [12,13]. Artificial intelligence enables real-time data processing, predictive model generation, and accurate measurement of industrial process indicators, leading to increased efficiency and cost reduction in food processing operations. In our ever-changing world, emphasizing safety and sustainability in food processing is crucial [14]. As consumers become more concerned about food quality and safety, there is a growing need for transparency and accountability in the food industry. This requirement calls for a structured approach and a clear supply chain to offer consumers detailed information about the origins, production methods, and environmental impact of the food they consume. This structured approach ensures that food is processed, handled, and stored in sanitary conditions to prevent illnesses and contamination, while also ensuring the safety and sustainability of food products. Prioritizing food safety and sustainability is not just a moral duty; it is also a strategic business necessity. Companies that give importance to these factors can build trust with consumers, gain a competitive advantage in the market, and contribute positively to societal well-being [15]. Additionally, such companies are better prepared to respond to evolving consumer preferences and demands. In conclusion, enhancing safety and sustainability in food processing is not only important but essential in today's world, meeting both ethical obligations and business imperatives. Despite challenges such as legislative and security concerns, the benefits of AI in food processing far outweigh the limitations, making it a valuable tool for the industry's advancement. This review explores how AI can address agri-food challenges such as food security, quality, and efficiency while considering environmental impacts. It examines how AI can transform agricultural production, processing, and distribution to support sustainable development and meet global population needs. Additionally, it evaluates the current adoption of AI in the food industry, identifies key applications, addresses challenges, and offers insights for future research and implementation.

2. Materials and method

For this review, the selection of relevant publications involved a thorough literature search utilizing "Web of Science," "Scopus," and "Google Scholar" databases. The search terms encompassed AI's role in the food industry and food safety, spanning publications from all years to the present. To streamline the

search, document types were narrowed down to "paper" or "review." Duplicate search results were consolidated, and research papers or reviews investigating AI powered food processing industry, food quality and safety were selected. A detailed flow chart outlining the literature search process can be referenced in Figure 1.

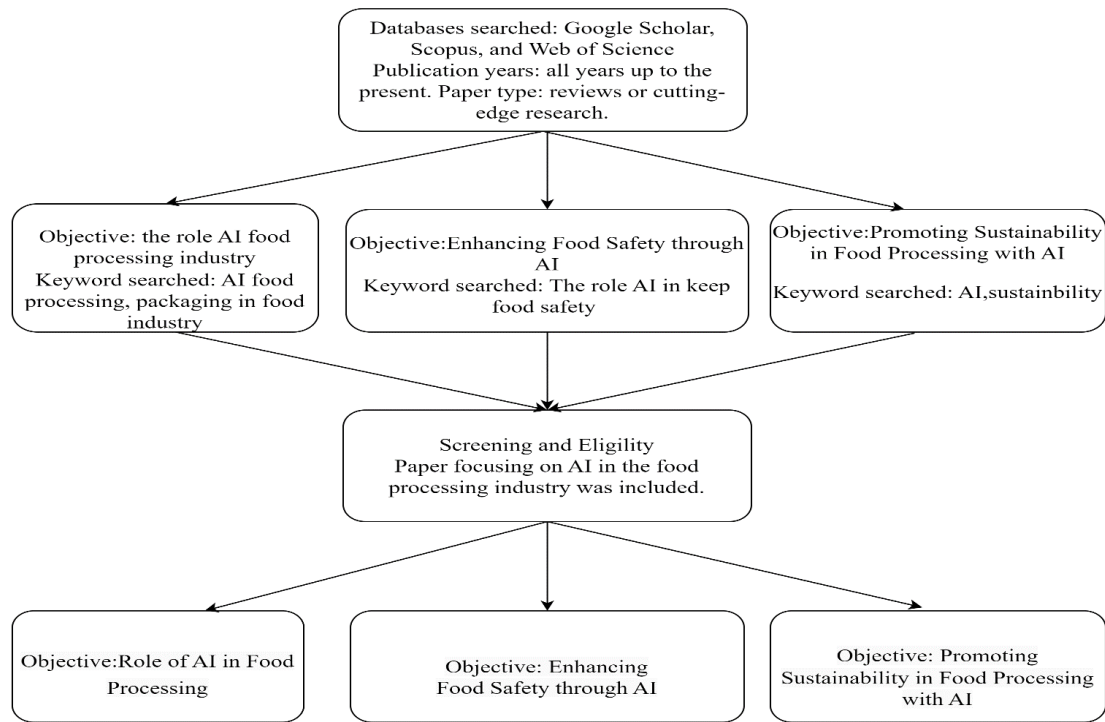


Figure 1. - Flow chart utilized to search for and choose papers incorporated within the review

2.1. Role of AI in Food Processing

The role of AI presents in figure 2, the food processing industry is vital for economies, influencing gross domestic product significantly. Raw food undergoes stages like sorting, grading, washing, processing, packaging, and marketing before reaching consumers, emphasizing the importance of cleanliness. AI algorithms provide efficient sorting solutions using methods like image acquisition and segmentation. Contamination risks during food transportation are considerable, prompting consideration of drones to mitigate them [16]. The food processing sector typically demands significant labor input, yet artificial intelligence offers potential to boost productivity and decrease wastage by substituting manual workers responsible for identifying unsuitable products

on the production line and quick decision-making requires the utilization of visual and olfactory senses, as well as the ability to adapt to evolving circumstances [17]. The food processing industry is impacted by factors like quality control, types of food, market trends, consumer preferences, and health considerations. These factors highlight the importance of adopting technologies to improve production standards, manage waste efficiently, and meet market demands effectively [18]. Currently, most food processing industries prioritize food quality, nutritional value, and processing techniques. This shift is driven by consumer expectations for foods that meet standards of quality, sensory appeal, and shelf life [19]. Within the food supply chain lies the processing cluster, employing techniques like heating, cooling, milling, smoking, cooking,

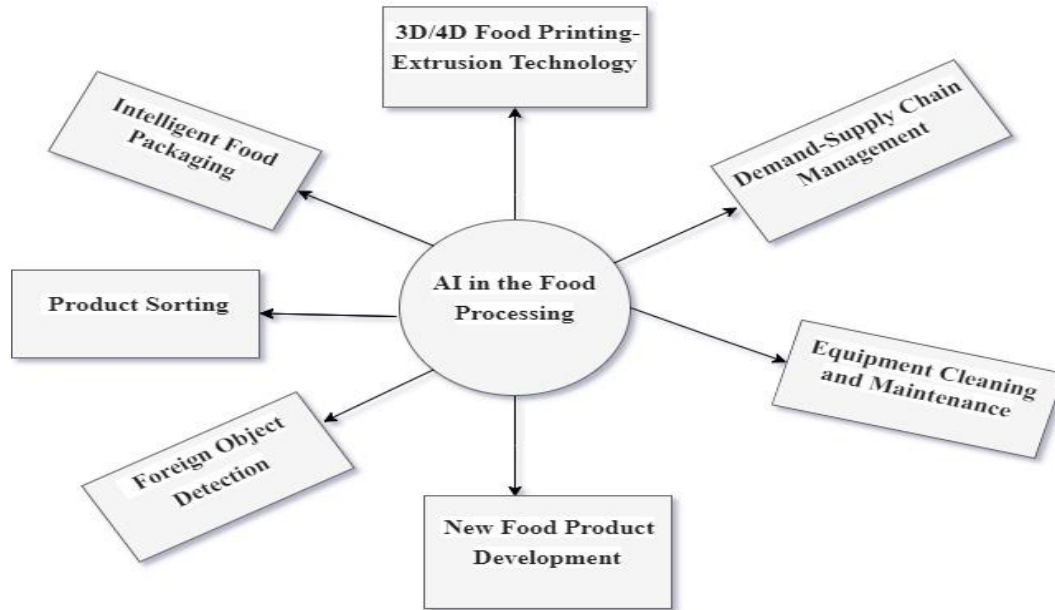


Figure 2 - Role of AI in the Food Processing.

and drying for agricultural products. Utilizing efficient parameters during this stage can yield high-quality food products while minimizing resource usage [7]. Artificial Intelligence enables food processing companies to automate food cataloging using cameras, lasers, and machine learning for efficient food sorting. For example, employing AI-based optical sorting solutions eliminates time-consuming processes for sorting fresh produce, resulting in higher yield, improved quality, and reduced wastage [20]. Artificial Intelligence plays a crucial role in the food industry, aiding in processing various food types using robots or machines. Maintaining hygiene is essential in food processing, focusing on personal and equipment cleanliness. Food safety regulations require manufacturing industries to closely monitor the food supply chain, a task made easier with AI, which meticulously oversees each stage, ensuring transparency to customers [19]. Food processing units can benefit from modernized methods like automatic mechanisms and advanced technologies such as artificial intelligence, machine learning, and internet of things, reducing the need for manual labor [21]. A cyber-physical twin can monitor food quality and packaging under various conditions throughout the food chain, including transportation and handling. This model considers quality parameters like sensory quality, chemical composition, economic

factors, and environmental impact. An artificial neural network model has been used to produce flour from watermelon pomace through the dehydration/drying process, emphasizing the importance of food quality in ensuring safe and nutritious food for food security. Food quality analysis during processing is crucial, with biosensors playing a significant role in conducting food analysis [2]. In the food industry, ordering and packaging tasks are typically time-consuming. Artificial Intelligence systems streamline these processes, minimizing errors and improving production efficiency. Yet, developing such systems is complex due to the variety in produce shapes, colors, and sizes. Successful AI sorting and packaging require extensive datasets. Presently, most sorting and packaging tasks are automated, using tools such as high-resolution cameras, lasers, X-rays, and infrared spectroscopy to inspect produce during input. This approach boosts production speed, enhances quality, and lowers labor expenses [3]. Efficient food sorting relies on comprehensive product analysis to inform processing decisions and attract customers. Top firms like TOMRA utilize advanced artificial intelligence for improved sorting accuracy via sensor-based systems, enhancing visual precision. This state-of-the-art technology, demonstrated in TOMRA's tomato sorting solutions, greatly enhances sorting efficiency and accuracy [22]. In the tomato ketchup processing, AI plays a

crucial role. Initially, the finest tomatoes and ingredients are carefully sourced and processed to craft the ultimate product. Here, a computer vision system takes charge, meticulously supervising the blending phase, precisely controlling factors like temperature, mixing speed, and timing for adding ingredients. Previously, manual inspection by workers was necessary, a method prone to errors, potentially leading to over-processing and financial setbacks. With the integration of machine vision technology, color and density are closely monitored throughout the heating and processing stages, simplifying batch testing and computations. Furthermore, Machine Vision data serves as valuable input for Deep Learning algorithms, enhancing predictive capabilities to identify the optimal moments for decision-making [23]. In pineapple juice production, AI technologies - including Machine Learning, Deep Learning, Computer Vision, and Robotics - are employed from fruit selection to packaging. Initially, Computer Vision ensures high-quality fruit selection, minimizing waste and manual labor. Deep Learning optimizes juice processing by automating sorting, grading, and mass estimation. Computer Vision maintains precision during mixing, preventing over-processing. In packaging, Computer Vision/Machine Vision ensures uniform filling, upholding quality standards. Robotics further enhances efficiency by palletizing products, reducing labor. Overall, AI integration revolutionizes pineapple juice production, improving quality, reducing costs, and boosting productivity [24].

AI technologies have transformed the food processing sector by enhancing efficiency, quality, and safety. AI's roles in food processing encompass quality assessment, predictive analytics, supply chain optimization, and personalized nutrition [8,19]. Collaborating with machine learning, AI contributes to enhancing food quality, nutritional value, and shelf life to meet consumer expectations [11]. Furthermore, AI methods facilitate real-time data processing and the creation of predictive models for precise monitoring of food industry parameters, ensuring product quality and safety [25]. Additionally, AI, especially through multi-layer perceptron networks, aids in

predicting and categorizing fruits and vegetables during drying processes, optimizing production efficiency and quality control [10]. In summary, AI applications in food processing streamline operations, minimize waste, and improve customer satisfaction in the food sector.

2.2. Enhancing Food Safety through AI

Ensuring food safety is vital for people's well-being, demanding the integration of state-of-the-art technology. Artificial intelligence and big data, fundamental components of the fourth industrial revolution, significantly shape the food industry [26,27]. They enhance production effectiveness, product standards, and nutritional content, while also reducing resource wastage. Ongoing research is investigating AI-based approaches to address dietary issues, particularly those linked to persistent health conditions like hypertension [28]. The food processing industry faces pressure to deliver safe, high-quality products meeting consumer expectations. Establishing reliable protocols to monitor product quality is crucial [29]. Food quality assessment covers internal and external factors. Workers handle external factors like surface color, texture, transparency, and defects, while internal aspects such as firmness, content, and acidity are assessed using conventional methods. Attributes like sweetness, flavor, and food safety, including risks such as bacterial contamination and pesticide residues, significantly impact food reliability. However, using traditional methods to evaluate these factors in today's food market is costly and time-consuming [30]. Ensuring food safety and quality is crucial in today's intricate food systems, from production to consumption. However, these processes often demand substantial labor. Embracing innovations such as machine vision can greatly boost food processing efficiency [5]. Adhering to regulations is vital to prevent contamination due to human error. The utilization of artificial intelligence in automated food processing offers a multifaceted approach to safeguarding food safety and quality. By mitigating contamination risks associated with microorganisms and chemical agents, it proactively prevents the occurrence of foodborne illnesses and the need for product recalls [27]. Integrating artificial intelligence into food supply chains further

strengthens this commitment to safety and quality. Artificial intelligence technologies provide unmatched capabilities in enhancing transparency, traceability, and addressing specific concerns like food safety, quality control, and waste reduction [31, 32]. This partnership not only protects consumer health but also shields food businesses from potential losses linked to product recalls and reputational harm. Quality control and food inspection practices are experiencing a paradigm shift propelled by artificial intelligence technologies. Automated systems, fueled by AI algorithms, are adept at promptly and precisely detecting pollutants, pathogens, and foreign matter in food products. This innovation significantly reduces the risk of foodborne illnesses while ensuring consumer safety remains paramount [33].

The crucial role of AI in predicting and preventing foodborne illnesses significantly impacts public health and safety. Artificial intelligence efficiently analyzes vast datasets from diverse sources, including food production records, weather patterns, and consumer health data [34]. This approach enables rapid risk identification and the establishment of early warning systems for foodborne illnesses. Through machine learning algorithms, AI detects complex patterns and emerging trends, pinpointing signs of contaminants or improper food handling practices. Health authorities and food regulatory bodies can then proactively respond by issuing recalls or enforcing strict safety measures to protect consumers. Artificial Intelligence facilitates real-time monitoring and analysis of food production facilities, promptly identifying deviations from safe practices and implementing corrective actions to prevent contamination. Integration with technologies like blockchain enhances traceability and supply chain management, ensuring transparency and accountability during outbreaks. Overall, AI's role in predicting and preventing foodborne illnesses holds significant potential for improving public health through risk identification and preventive actions. By harnessing AI technology, we can effectively analyze extensive datasets, enabling swift responses to emerging risks and strengthening prevention strategies. As AI advances, its importance in upholding food safety will continue to grow,

emphasizing its critical role in safeguarding consumers globally. Artificial Intelligence has significantly advanced food safety on multiple fronts. It has been used to predict food fraud risks using interpretable AI methods like Local Interpretable Model-agnostic Explanations (LIME), Shapley Additive explanations (SHAP), and What if Tool (WIT) to interpret machine learning forecasts [34]. Additionally, AI plays a crucial role in improving food hygiene and safety by facilitating continuous monitoring of environmental cleanliness, staff, and food standards, thereby enhancing overall food safety and quality standards [35]. Furthermore, AI's impact extends to transforming the agricultural and food sector, changing precision agriculture, crop monitoring, predictive analysis, streamlining supply chains, food processing, quality control, personalized nutrition, and, importantly, food safety [8]. These examples highlight AI's significant impact on advancing food safety practices.

2.3. Promoting Sustainability in Food Processing with AI

To shift global food consumption patterns toward sustainability and increase productivity in the food production chain, it is critical to draw on insights from other sciences. This includes implementing artificial intelligence-based technologies [36]. The food processing industry plays a crucial role in meeting the increasing demands of a growing global population. However, it also contributes to environmental problems such as greenhouse gas emissions, water pollution, and deforestation [37]. To address these challenges and promote sustainability, the integration of artificial intelligence in food processing can be a game-changer. AI can help optimize production processes, reduce waste, and minimize resource consumption [38]. By leveraging AI technology, food processors can improve efficiency and minimize their environmental impact. AI-powered algorithms can analyze data from various sources to optimize energy consumption, waste management, and supply chain logistics in food processing [39]. Additionally, AI can help in the development of sustainable packaging solutions by analyzing materials and designs that are eco-friendly and recyclable [38]. By

incorporating AI technologies into food processing, companies can enhance traceability through blockchain for credible sourcing and improve quality forecasting with big data analysis. This integration of AI in food processing can enable smarter decision-making, leading to more sustainable practices and a reduced ecological footprint [39]. By harnessing the power of artificial intelligence, food processors can revolutionize the industry and align it with sustainability goals. Overall, the integration of AI in food processing has the potential to revolutionize the industry and promote sustainability by optimizing production processes, reducing waste, improving traceability, and fostering eco-friendly practices [38]. By harnessing the power of AI, companies in the food processing industry can not only enhance their efficiency and productivity but also contribute to a more sustainable and environmentally friendly future. Furthermore, AI can also be utilized in smart warehouses to optimize inventory management and increase productivity, leading to more efficient supply chains and reduced waste. By utilizing AI in food processing, companies can improve their traceability systems and address the challenges posed by the variety of raw materials, batch mixing, and quality forecasting. Additionally, the integration of AI with other technologies such as electronic nose, electronic tongue, computer vision systems, and near infrared spectroscopy can further enhance the capabilities of AI in the food industry, allowing for more accurate food quality determination, control tools, and classification of food. Artificial Intelligence algorithms optimize the food supply chain by enhancing demand projection, inventory management, and logistics. By analyzing extensive datasets including historical sales, weather trends, and consumer preferences, these technologies accurately predict future demand. This results in efficient production, less food waste, improved inventory management, and ultimately cost savings for businesses, promoting a sustainable food ecosystem [40].

2.4. Challenges and Limitations

Although AI technology brings numerous benefits, it also presents notable challenges. One pressing social issue is the potential rise in

unemployment as intelligent machines and robots take over repetitive tasks, potentially reshaping traditional employment landscapes. Additionally, technological constraints become apparent as machines operate within predefined parameters and may malfunction or produce inaccurate outputs if pushed beyond their programmed capacities.

The other challenges to AI adoption are technological, particularly data availability and quality. Unreliable data, or the need to collect it, limits future applications. Furthermore, the necessary infrastructure has yet to be established, which will take a significant amount of time to complete [41]. Moreover, the considerable costs associated with developing and maintaining advanced AI systems create significant barriers. Continuous updates are crucial to keep pace with evolving AI standards, further straining the finances of organizations and industries embracing these technologies [42].

The integration of artificial intelligence in the food processing industry has brought numerous advancements and benefits [38]. However, it is important to acknowledge the challenges and limitations that AI faces in this sector. These challenges include the complexity of food processing tasks, the need for large amounts of quality data, and ensuring the safety and reliability of AI systems. Another challenge is the potential ethical implications of using AI in food processing, such as concerns about privacy and data security. Furthermore, the lack of technical expertise and resistance to change among food processing industry professionals may pose challenges to implementing AI systems effectively. Additionally, the adaptability of AI algorithms to different types of food processing operations and variations in raw materials can also be a limitation. Furthermore, the high initial cost of implementing AI systems and the ongoing maintenance and training required can be a barrier for smaller food processing companies [40]. Overall, while AI offers great potential in the food processing industry, addressing these challenges and limitations is crucial to ensure its successful implementation and utilization. To address these challenges and limitations, it is important for stakeholders in the food processing industry to invest in research and development to improve AI algorithms

specifically tailored for food processing industry.

2.5. Future Directions and Opportunities

Future directions and opportunities of AI in food processing include enhancing efficiency and productivity, improving food safety and quality control, reducing food waste, and developing personalized nutrition solutions. Artificial Intelligence has the potential to revolutionize the food processing industry by enhancing efficiency, increasing productivity, and ensuring better food safety and quality control measures [43]. Artificial Intelligence can also play a crucial role in reducing food waste through smart inventory management systems and optimized production processes. Furthermore, AI has the potential to transform personalized nutrition by analyzing individual dietary needs and preferences to create tailored eating plans and recommendations. Additionally, AI can help in identifying and predicting trends in consumer preferences, enabling food processing companies to innovate and develop new products that better meet customer demands. The integration of AI in the food processing industry holds promise for significant advancements in efficiency, safety, waste reduction, and customer satisfaction. Moreover, Industry 4.0 concepts can be applied to the food processing industry, facilitating intelligent manufacturing processes and optimizing the entire supply chain from production to distribution. By leveraging AI capabilities, food processing companies can achieve improved efficiency and productivity, resulting in cost savings and faster production rates. In conclusion, the future of AI in food processing shows great potential for enhancing various aspects of the industry, from efficiency and productivity to safety and waste reduction. The application of AI in the food processing industry has the potential to revolutionize efficiency, productivity, food safety and quality control, waste reduction, and personalized nutrition solutions [44]. Artificial Intelligence has the potential to transform the food processing industry by enhancing efficiency, increasing productivity, and ensuring better food safety and quality control measures. Additionally, AI can aid in identifying and predicting consumer preference trends to develop new products that better cater to

customer demands. The integration of AI in the food processing industry offers the potential for significant advancements in efficiency, safety, waste reduction, and customer satisfaction, ultimately leading to a more competitive and successful food processing industry. Furthermore, applying Industry 4.0 concepts in the food processing industry can result in intelligent manufacturing processes, optimized supply chains, and enhanced overall operations. Through the utilization of AI technology, the food processing industry can achieve improved efficiency, safety, waste reduction, and customer satisfaction. Despite facing challenges, the incorporation of AI in food processing offers numerous benefits. These advanced technologies enhance different facets of food processing, such as quality control and decision-making, leading to a notable improvement in efficiency and productivity. Moreover, AI plays a crucial role in guaranteeing food safety through early contaminant detection and providing personalized nutrition based on individual dietary needs. Furthermore, this integration actively supports sustainability initiatives by optimizing resource utilization and reducing waste generation [40]. Overall, the integration of AI in the food processing industry has the potential to drive significant advancements in efficiency, safety, waste reduction, and customer satisfaction, revolutionizing the industry.

3. Conclusion

In conclusion, the projected global population surge to 9.7 billion by 2050 underscores the critical imperative of securing food amidst the complex interplay of factors like population growth, climate change, and resource depletion. Artificial Intelligence emerges as a pivotal ally in this endeavor, offering tailored solutions to enhance food safety, quality management, and productivity. This review underscores the indispensable role of AI in tackling the challenges faced by the food processing sector, highlighting its profound impact on efficiency, quality, and sustainability. Through applications like image processing, robotics, and AI-driven fertilizer management, AI significantly shapes food safety, quality assurance, and waste reduction. Its integration into food processing holds the

promise of transforming industry standards, addressing tasks ranging from product categorization to personalized nutrition. However, it's imperative to address challenges such as job displacement, technical limitations, and ethical considerations. Despite these hurdles, the potential of AI to advance sustainability, ensure food safety, and cater to consumer needs is significant. Artificial Intelligence stands poised to enhance efficiency, stimulate innovation, and promote sustainability in food processing, effectively catering to the needs of a growing global population. Looking forward, AI offers a promising trajectory for the food processing industry, reshaping conventions and navigating 21st-century challenges with resilience and ingenuity.

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