*Review Article*

Harnessing AI and Emerging Technologies for Sustainable Food Systems: Innovations in Automation and Intelligent Production

**ABSTRACT**

The global food system faces challenges in food security, environmental sustainability, and supply chain inefficiencies, with traditional methods struggling to meet demands while minimizing resource depletion and ecological impact. New approaches that integrate AI and new technologies must be developed to address the growing concerns of global food security and sustainability. This article reviews the potential progressive roles of automation, artificial intelligence, and renewable energy for maintaining sustainable practices, optimizing food production, and enhancing decision-making. Blockchain technology improves transparency and traceability in food supply chains. IoT-powered smart systems enable real-time monitoring of crops, livestock, and food storage conditions, optimizing resource usage. AI-driven developing algorithms enhance decision-making, automate agricultural processes, and improve food quality and safety. While renewable energy sources like solar-powered aquaponics and hybrid energy systems promote ecologically sustainable food production, robotics and 3D printing are developing agricultural processes. However, widespread adoption faces challenges such as high costs, infrastructure limitations, and regulatory barriers alongside these benefits. Future research should focus on enhancing AI-driven solutions, addressing scalability issues, and ensuring equitable access to these technologies across AI ethics, infrastructure, and regulatory framework.

***Keywords:****AI in food systems, automation, IoT, renewable energy, sustainable food technology*

### INTRODUCTION

### The global food system is undergoing considerable changes as a result of growing concerns such as population expansion, climate change, resource depletion, and food scarcity. Although they were successful in the past, traditional agricultural practices are currently having trouble meeting the rising need for food supply without endangering environmental sustainability (Khatri et al., 2023). The advent of cutting-edge technology, such as automation, artificial intelligence (AI), the Internet of Things (IoT), and renewable energy, offers encouraging ways to maximize food production, improve supply chain effectiveness, and support sustainable farming methods (Duguma & Bai, 2024; Kumar et al., 2024). The food business may boost output, cut waste, and enhance overall food security by incorporating these technologies. AI, including machine learning and deep learning, is crucial for applications like crop disease detection and supply chain optimization, utilizing neural networks for complex pattern analysis (Kumari et al., 2023).

### 1.1 Global Challenges in Food Systems

### Due to interconnected causes like fast population increase, climate change, and depleting natural resources, food security and sustainability are two of the 21st century's most urgent concerns. The need for food is expected to rise exponentially when the world's population approaches 10 billion people by 2050 (Simane et al., 2025). However, issues like harsh weather, water scarcity, soil degradation, and biodiversity loss limit our ability to meet this demand. Unpredictable weather patterns brought on by climate change, such as droughts and floods, impair agricultural output and cause food shortages and price instability. Food waste is also a result of antiquated supply chain management and ineffective farming practices. It is estimated that inefficient handling, storage, and distribution practices result in the loss or waste of almost one-third of the world's food production (Hassan et al., 2025). It is challenging for small-scale farmers in developing countries to compete in the market because of issues such restricted access to modern equipment, inadequate infrastructure, and financial limitations. Overuse of fertilizers and pesticides degrades soil quality and compromises food safety. In order to improve food production, maximize resources, and create sustainable food systems, technologically advanced solutions are required.

### 1.2 Emerging Technologies in Food Systems

### Emerging technologies are being widely implemented to improve agricultural techniques and food production systems in order to address the urgent issues of sustainability and food security. Precision agriculture is now using AI and machine learning algorithms to evaluate data on crop health, soil composition, and climate conditions, enabling farmers to make data-driven decisions (Debnath et al., 2024; Mohyuddin et al., 2024). By optimizing the use of herbicides, fertilizers, and water, these solutions reduce waste and boost yield efficiency. Drones and IoT-enabled smart sensors work together to monitor farmlands in real time, guaranteeing the best possible nutrient and irrigation management (Shahab et al., 2024). Robotics and automation are changing labor-intensive agricultural operations by increasing productivity and lowering dependency on human labor (Hoque & Padhiary, 2024). By improving food traceability and supply chain transparency, blockchain technology lowers fraud and ensures food safety. A growing number of food production systems are incorporating renewable energy sources, such as wind and solar electricity. Aquaponic farming methods and solar-powered irrigation systems are offering sustainable substitutes for traditional energy-intensive farming practices (Zamnuri et al., 2024). When combined, these cutting-edge technologies offer a viable route to a world food system that is more resilient, effective, and ecologically sustainable.

### 1.3 Objectives and Scope

### This review examines the role of automation, artificial intelligence, and renewable energy in changing food systems. It highlights the importance of these technologies in ensuring resilience, efficiency, and sustainability in the face of increasing food demand and environmental concerns. AI-driven food production uses machine learning and developing research for real-time crop monitoring, insect identification, and yield forecasting. IoT-enabled smart decision-making ensures precision agriculture through sensors, drones, and automated systems. Robotics and automation are crucial in mechanizing labor-intensive tasks like planting, harvesting, sorting, and packing for cost-effective and precise food production. Renewable energy integration, such as solar, wind, and hybrid systems, can lower carbon footprints and advance sustainable agricultural and food processing methods. Blockchain technology can improve quality control, minimize food loss, reduce fraud, and improve food traceability. The review highlights the potential of AI and cutting-edge technologies in creating a future-ready, intelligent, and sustainable global food ecosystem, addressing food security, resource limitations, and environmental impact.

### ****AI IN FOOD SYSTEMS****

### The global food sector is undergoing a change driven by AI, which is increasing productivity, sustainability, and efficiency (Marvin et al., 2022). AI-driven solutions use automation, machine learning, and data analytics to tackle urgent issues like supply chain inefficiencies, resource waste, shifting market demand, and climate change. Applications of AI in logistics, food processing, and agriculture enable data-driven decision-making that improves food security and lessens its negative effects on the environment (Dhal & Kar, 2024).For example, AI-powered precision farming has led to 20-25% yield improvements through predictive analytics and resource management (Thangamani et al., 2024). AI-driven logistics and data analytics have contributed to a 20-30% reduction in food waste through better supply chain optimization (Vlăduț & Ungureanu, 2024).

### 2.1 Intelligent Food Production

### AI-driven food production processes are replacing traditional methods, utilizing massive datasets from sensors, climate models, and satellite imagery to predict crop yields, identify diseases, and recommend best farming practices (Waseem et al., 2024). This technology increases productivity while reducing the use of pesticides, fertilizers, and water. AI-powered equipment monitors crops, optimizes planting and harvest dates, and detects risks through automated pest and disease identification. Deep learning algorithms like Convolutional Neural Networks (CNNs) enhance precision agriculture by analyzing satellite and drone imagery to detect crop diseases, while Generative Adversarial Networks (GANs) simulate climate impacts on crop yield (Peng et al., 2024). AI promotes ecologically friendly farming methods by facilitating early intervention and reducing pesticide use. AI-driven mobile applications provide real-time notifications for farmers to protect crop health. AI-powered robotics handle labour-intensive operations like automated harvesting, sorting, and precise planting, recognizing ripe produce, collecting fruits and vegetables with minimal damage, and expediting post-harvest procedures (Zahoor et al., 2024). These robots increase productivity, cut costs, and improve food production sustainability by decreasing reliance on physical labour. AI-driven image recognition and computer vision systems are used in manufacturing facilities to check food products for flaws, contamination, and irregularities, improving food safety and reducing waste. Table 1 provides an overview of AI applications in agriculture, detailing key technologies, their functions, benefits, and real-world examples. It covers statical analysis for crop yield forecasting, AI-powered robotics for automated harvesting, and smart irrigation systems for water management​. Whereas Figure 1 illustrates an AI-powered smart farming system, demonstrating the integration of AI with IoT sensors for real-time monitoring and decision-making in agricultural processes.

### Table 1. AI applications in agriculture

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| AI Technology | Function | Benefits | Example Use Cases | References |
| Predictive analytics | Crop yield forecasting | Reduces waste, optimizes planting | AI-based weather prediction | (Assimakopoulos et al., 2024) |
| Automated pest detection | Identifies pests & diseases | Reduces pesticide use | Computer vision for crops | (Abbaspour-Gilandeh et al., 2022) |
| AI-powered robotics | Automated harvesting | Improves efficiency, reduces labour costs | Robotic fruit pickers | (Musa et al., 2023; Padhiary, Roy, et al., 2024) |
| Quality control | Detects food defects | Ensures high food safety | AI-based food inspection | (Vegesna et al., 2024) |
| AI in irrigation | Smart water management | Conserves water, boosts yield | IoT-enabled smart irrigation | (Et-taibi et al., 2024; Padhiary, 2024b) |
| Soil health analysis | Evaluates soil nutrients | Reduces excessive fertilizer use | AI-powered soil scanners | (Javaid et al., 2023) |
| AI in food processing | Automated sorting & packaging | Reduces manual labour, speeds up production | AI-driven packaging robots | (Amertet et al., 2023) |
| AI for supply chain | Inventory & logistics planning | Minimizes food waste, enhances efficiency | AI-based demand prediction | (Aldoseri et al., 2024; Barnavo Das et al., 2025) |
| AI in food safety | Detects contamination risks | Reduces foodborne illnesses | AI-powered food monitoring | (Chhetri, 2024) |
| AI-driven decision support | Provides insights for farmers | Enhances productivity | AI-based farm management software | (Elbasi et al., 2024) |

### 

### Figure 1. AI-powered smart farming system

### 2.2 Smart Decision-Making with IoT and Sensors

### Artificial intelligence and the Internet of Things are developing food production decision-making by providing real-time insights that improve sustainability and efficiency. Data is continuously gathered from agricultural fields, greenhouses, and food storage facilities using IoT devices like smart sensors, drones, and automated monitoring systems (Hoque et al., 2025; Laskar, 2024). AI algorithms process this data to identify abnormalities, allocate resources optimally, and increase operational efficiency. Smart irrigation systems use AI-driven analytics to manage water usage based on real-time soil moisture levels, weather forecasts, and crop requirements. Reinforcement learning algorithms optimize irrigation scheduling by adjusting water distribution based on soil moisture data and real-time weather conditions (Zhao et al., 2023). Climate and soil monitoring uses IoT sensors to provide farmers with practical advice on crop rotation, planting dates, and fertilizer. Remote monitoring IoT solutions, powered by solar power, are particularly useful in areas with poor electrical access. AI is also essential for supply chain management and food logistics, using IoT-generated data for developing research , improving food storage conditions, and expediting delivery logistics (McDonald, 2024). Machine learning models analyse past sales data, meteorological trends, and consumer behaviour to predict changes in demand and minimize food waste.

### 2.3 AI-Driven Sustainability Insights

### AI enhances food system sustainability by assessing resource use and waste, allowing farmers to adopt more efficient techniques that have a lower environmental impact. Food waste can be decreased by using statistical analysis driven by Recurrent Neural Networks (RNNs) to forecast changes in demand based on previous food production data (Han et al., 2023). One important way to increase resource efficiency is through precision agriculture. AI-driven farm management systems offer real-time suggestions on how best to apply irrigation, insecticides, and fertilizers (Rabha et al., 2024). AI reduces chemical runoff, stops soil erosion, and improves biodiversity by making sure that just the required number of resources are used (Padhiary, Tikute, et al., 2024). AI-driven food waste reduction is another important sustainability application. AI-driven inventory management systems monitor expiration dates, identify bottlenecks in the supply chain, and make recommendations on ways to reduce food waste (Gul & Morande, 2024). Eco-friendly packaging options and biodegradable material identification are being provided by machine learning algorithms. Waste management facilities' AI-driven sorting systems effectively separate recyclables, cutting down on landfill waste and encouraging environmentally friendly packaging techniques (Olawade et al., 2024). Food traceability and transparency are being improved by blockchain-integrated AI systems, guaranteeing that consumers may obtain precise information regarding the provenance, quality, and sustainability of their food. Every step of the food supply chain is tracked by blockchain solutions driven by AI, which also ensures adherence to sustainability requirements, prevents fraud, and reduces food waste through improved inventory management (Omar et al., 2024). Table 2 lists AI-driven sustainability practices, their benefits, and implementation challenges.

### Table 2. AI-driven sustainability practices

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sustainability Practice | AI Role | Benefits | Implementation Challenges | References |
| Precision agriculture | AI-driven soil & crop monitoring | Reduces resource waste, increases yield | High initial costs | (Padhiary et al., 2025) |
| Food waste reduction | AI-based inventory management | Reduces spoilage & overproduction | Requires accurate data | (Jariwala, 2025) |
| Blockchain traceability | Tracks supply chain data | Improves transparency, prevents fraud | Adoption resistance | (Friedman & Ormiston, 2022) |
| Smart packaging | AI-enhanced expiration tracking | Extends shelf life, reduces waste | Implementation costs | (Ikram et al., 2024) |
| AI in sustainable farming | Data-driven climate adaptation | Increases resilience, optimizes resources | Limited farmer training | (Usigbe et al., 2023) |
| AI in alternative proteins | Enhances production methods | Supports plant-based food growth | High research costs | (Alasi et al., 2024) |
| AI for circular economy | Recycles food & packaging waste | Reduces landfill impact | Complex waste processing | (Onyeaka et al., 2023) |
| AI in energy efficiency | Optimizes energy use in food processing | Lowers carbon footprint | High investment costs | (Chen et al., 2021; Padhiary, 2023) |
| AI-driven supply chain | Reduces transportation emissions | Cuts food miles, enhances efficiency | Requires infrastructure | (Anwar et al., 2023) |
| AI for biodiversity | Monitors ecosystems | Helps conservation & sustainable land use | Limited data availability | (Shivaprakash et al., 2022) |

### ****AUTOMATION IN FOOD AND AGRICULTURAL PROCESSES****

Automation enhances food and agricultural systems by increasing productivity, improving precision, and reducing human labour dependency (Bazargani & Deemyad, 2024). Traditional farming methods often involve high human labour, leading to inefficiencies and inconsistent food quality. Advances in robotics, AI-driven mechanization, IoT-integrated smart systems, and 3D printing have made food production and processing more efficient. Automation can address issues like food waste, post-harvest losses, labour shortages, and environmental sustainability. Robotics in food processing ensure high quality standards, while automated farming equipment increases precision and reduces waste(Caldwell, 2023).

### 3.1 Robotics in Food Production

Robotics has changed traditional agricultural methods by increasing productivity, accuracy, and sustainability. Advances in automation, computer vision, and artificial intelligence (AI) have enabled robots to perform tasks that once required human labor, such as planting, watering, harvesting, sorting, packing, and food processing(Thakur et al., 2023)**.** These robots improve efficiency, preserve food quality, reduce reliance on physical labor, and minimize human error (Hoque, Padhiary, et al., 2025). AI-driven robots equipped with high-resolution cameras and deep learning algorithms enable real-time crop maturity detection, disease detection, and resource allocation optimization (Ayoub Shaikh et al., 2022).

Autonomous harvesting robots are crucial for identifying ripe and unripe crops using AI-powered computer vision, ensuring optimal crop harvesting and minimizing spoilage. Precision seeding and planting robots increase crop yields by minimizing seed waste and planting seeds at precise depths and distances. AI-powered weeding and pest management robots can differentiate between crops and weeds, administering herbicides only where needed or using non-chemical methods like laser weeding (Taneja et al., 2023). Automated feeding devices and robotic milking systems have increased productivity, simplified processes, and ensured animal welfare in dairy and cattle sectors. Post-harvest procedures like sorting, grading, and packaging are mechanized using AI-driven vision technology. AI-driven food processing robots automate tedious processes, reducing contamination risk while maintaining efficiency and hygiene in manufacturing facilities (Liberty et al., 2024). Robotics technology is poised to significantly transform food production by boosting automation, optimizing resource utilization, and strengthening resilience and sustainability. **Table 3** presents the impact of automation on food production, highlighting key technologies, their functions, benefits, and associated challenges.

**Table 3.** Impact of automation on food production

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Automation Technology | Function | Benefits | Challenges | References |
| Robotic harvesters | Automated crop picking | Reduces labour costs, improves efficiency | High initial investment | (Cheng et al., 2023) |
| Autonomous tractors | Precision ploughing & seeding | Optimizes land use, saves time | Requires advanced training | (Padhiary, Kumar, et al., 2024; Qu et al., 2024) |
| AI-powered sorting machines | Automated food grading | Ensures consistent quality | Requires maintenance | (Onyijen et al., 2024) |
| Automated irrigation | Smart water management | Saves water, boosts crop yield | Sensor calibration issues | (Touil et al., 2022) |
| Drone monitoring | Aerial crop health analysis | Reduces manual inspection time | Weather-dependent operation | (Mishra et al., 2023) |
| Smart greenhouses | AI-controlled climate systems | Maximizes production efficiency | High energy requirements | (Pimenow et al., 2024) |
| Automated packaging | AI-driven food packing | Reduces contamination risks | Equipment costs | (Zatsu et al., 2024) |
| Food processing robotics | AI-assisted processing | Increases production speed | Limited adaptability | (Bidyalakshmi et al., 2024a) |
| AI in dairy automation | Robotic milking machines | Enhances dairy yield & hygiene | Expensive for small farms | (Shamsuddoha & Nasir, 2025) |
| Autonomous transport | AI-powered delivery logistics | Reduces food waste & fuel use | Regulatory concerns | (Shobhana, 2024) |

### 3.2 Mechanized Systems for Post-Harvest Processing

### Post-harvest processing has been significantly improved by automation and AI-powered technology, leading to increased food safety, productivity, and financial returns. Automated sorting and grading systems classify food items based on size, colour, ripeness, and defects, ensuring only high-quality food reaches the market (Chakraborty et al., 2023). Advanced robotic arms with AI-powered image identification prevent defective products from entering the supply chain. Precision cleaning equipment and smart sprayers maintain food cleanliness through controlled disinfectant or organic treatment dosages. IoT-enabled cold storage and monitoring systems preserve perishable goods, while smart sensors track environmental parameters and adjust storage conditions to prevent spoilage. Blockchain technology and artificial intelligence enhance traceability and food safety across the supply chain (Chandan et al., 2023). Automated packaging and quality control technologies further accelerate post-harvest processing by reducing human interaction and optimizing material use. Machine vision technology inspects food goods for defects before sealing them in protective packaging (Lario et al., 2025). Some smart packaging options even have built-in sensors to monitor temperature exposure, freshness, and expiration signs in real time.

### 3.3 Integrating 3D Printing in Agricultural Robotics

### 3D printing is improving farming by enabling quick prototyping, economical production, and customization of farming equipment and instruments (Padhiary, Barbhuiya, et al., 2024). This technology lowers costs and ensures smooth operations by allowing farmers and agricultural engineers to design, build, and repair components as needed. 3D-printed robotic arms and grippers are being developed for delicate harvesting operations, while precision instruments like drone parts, irrigation nozzles, and seed dispensers are being developed (Jin et al., 2021). Small-scale farmers benefit from this capability, as they can print necessary farming implements locally instead of relying on expensive imports or mass-produced substitutes. 3D food printers are producing lab-grown protein structures, plant-based meat alternatives, and nutrient-rich meals, meeting the growing demand for sustainable food sources (Arja, 2024). Biodegradable packaging made with 3D printing is also being used in vertical and urban farming to construct modular hydroponic and aeroponic systems, optimizing food production in constrained areas.

### ****RENEWABLE ENERGY IN FOOD PRODUCTION****

### The food industry is one of the largest energy consumers with agriculture, food processing, transportation and storage relying heavily on non-renewable energy sources such as fossil fuels. This dependence leads to high greenhouse gas emissions, rising operational costs and environmental degradation, making the transition to renewable energy sources a necessity (Hai Alami et al., 2024). Renewable energy sources, such as solar, wind, bioenergy and hydropower, offer sustainable alternatives to fossil fuels, ensuring cost-efficient, low-emission and resilient food production systems. These technologies help reduce energy consumption, improve food security and support climate-friendly agriculture, making food production more efficient, eco-friendly and economically viable (Gunduz, 2023). This section explores the impact of renewable energy on food systems, focusing on solar-powered food and aquaculture systems, hybrid energy technologies, and energy efficiency optimization in food supply chains.

### 4.1 Solar-Powered Systems for Food and Aquaculture

### Solar energy is the most commonly used renewable energy source in food and agriculture due to its abundance, cheap operational costs, and sustainability. The use of solar-powered farming, food processing, and aquaculture systems has greatly decreased dependency on fossil fuels, increasing the efficiency and affordability of food production (Roy et al., 2025). Figure 2 illustrates the working mechanism of AI-integrated solar irrigation systems, showcasing how solar power and AI-driven automation optimize water distribution.

### *Solar-Powered Irrigation Systems:* Irrigation is one of the most energy-intensive agricultural processes, particularly in areas with high water demand and little rainfall. Conventional irrigation systems use electric or diesel pumps, which raise fuel prices and produce carbon emissions (Maniruzzaman et al., 2025). By using photovoltaic panels to power water pumps, solar-powered irrigation makes sure that crops receive water without becoming more reliant on fuel (Verma et al., 2021). Cutting-edge AI-based irrigation systems combine climatic data and soil moisture sensors to maximize water distribution, avoiding water waste and guaranteeing effective irrigation.

### *Solar Aquaponics and Hydroponics:* Innovative food production techniques like hydroponics and aquaponics necessitate constant nutrient monitoring, aeration, and water circulation (Ibrahim et al., 2023). Solar-powered systems enable farmers to run their operations effectively using renewable energy, yet grid electricity can be expensive and unsustainable (Padhiary, 2024a). These food production techniques are now more widely available and scalable because to solar-powered pumps, aerators, and filtration systems that lower electricity costs while preserving ideal growing conditions for aquatic and plant life.

### *Solar Drying for Food Preservation:* Food deterioration caused by inadequate storage and drying practices results in considerable post-harvest losses in many countries. Fuel-based heat sources are used in conventional food drying techniques, which raises energy expenses and pollutes the environment (Sonowal, 2025). Solar drying systems effectively remove moisture from food items using ventilation fans and solar heat collectors, maintaining nutritional value and increasing shelf life (Rahman et al., 2025). For small-scale farmers and food processors in rural locations without access to reasonably priced electricity, this is especially advantageous.

### *Solar Cold Storage and Refrigeration:* In remote and off-grid locations, maintaining cold storage for perishable goods like dairy, fruits, vegetables, and seafood necessitates a constant power source, which can be expensive (Amjad et al., 2023). In order to maintain ideal temperatures, avoid spoiling, and minimize food loss, solar-powered cold storage systems make use of energy-efficient cooling technology and battery storage. These techniques are especially helpful in developing nations, where a lack of energy causes large food losses.

### *Solar-Powered Greenhouses:* Stable energy sources are necessary for heating, cooling, and lighting in controlled-environment agriculture, such as greenhouse farming (Engler & Krarti, 2021). In order to ensure energy efficiency and higher crop yields, solar-powered greenhouses use AI-driven climate management systems to monitor temperature, humidity, and CO₂ levels (Selvam & Al-Humairi, 2023). By lowering reliance on fossil fuels, these greenhouses improve farming's sustainability and climate change adaptability.

### Figure 2. Solar-powered irrigation system

### 4.2 Hybrid Renewable Energy Systems

### While solar energy is a potent renewable resource, it has limitations, such as decreased efficiency on overcast days or at nighttime. Hybrid renewable energy systems integrate several energy sources, including solar, wind, and bioenergy, to improve food production's resilience and dependability and guarantee a steady supply of power (Majeed et al., 2023a).

### *Solar-Wind Hybrid Systems:* Wind turbines supplement solar panels by producing electricity when solar energy generation is minimal, such as at night or during cloudy days (Hasan et al., 2023). For isolated agricultural regions and food processing facilities that need continuous energy to function, hybrid solar-wind farms are especially advantageous. These technologies increase total energy efficiency and dependability by ensuring continuous irrigation, automated farming practices, and food processing.

### *Bioenergy from Agricultural Waste:* Organic waste from agriculture, including crop residues, animal dung, and byproducts of food production, is produced in significant quantities (Ashokkumar et al., 2022). Anaerobic digestion and biomass gasification can be used to transform this waste into biogas, biofuels, or electricity. AI-powered bioenergy systems maximize the conversion of waste into energy while lowering fuel costs, greenhouse gas emissions, and waste disposal costs (Kunatsa, 2025).

### *Microgrids for Rural Farming Communities:* Many agricultural areas in underdeveloped nations do not have consistent access to electricity, which makes it difficult to produce food, store perishable commodities, or irrigate crops. Solar, wind, and bioenergy-powered microgrids provide decentralized energy solutions and lessen reliance on pricey diesel generators (Zhou, 2022). In rural locations, these systems facilitate economic growth, energy independence, and sustainable food production.

### *Hydropower for Water-Intensive Agriculture:* The pumping and distribution of water is a major energy-intensive activity in some food production systems, including fish farming, rice farming, and water-intensive crop irrigation (Brears, 2023). These farming systems are more sustainable and energy-efficient because to the steady supply of renewable electricity from small-scale hydropower facilities. A vital part of sustainable food production, hybrid renewable energy systems increase energy security, lower carbon footprints, and boost agricultural resilience.

### 4.3 Energy Optimization in Food Supply Chains

### Food manufacturing, processing, packaging, distribution, transportation, and cold storage are all parts of the energy-intensive food supply chain. Optimizing energy use along the whole supply chain has become crucial for guaranteeing sustainability, affordability, and food security as a result of the world's expanding food demand and rising energy prices (Michel et al., 2024). Reducing greenhouse gas emissions, cutting operating costs, and avoiding food loss and waste all depend on the utilization of renewable energy, AI-driven monitoring systems, and energy-efficient processing technology (Morkūnas et al., 2024). The food industry can make the shift to a low-carbon, resource-efficient, and climate-resilient system by incorporating cutting-edge energy management technology.

### *AI-Driven Smart Energy Management:* AI-powered smart energy management systems are crucial for food production, processing, and distribution facilities (Manoharan et al., 2024). These systems use IoT-connected sensors, machine learning algorithms, and developing algorithms to measure energy consumption in real time, identify inefficiencies, and suggest automated changes to reduce power waste. They can reduce electricity usage without compromising food safety by anticipating peak energy demand and dynamically adjusting loads for refrigeration, heating, ventilation, and lighting. AI-driven predictive maintenance tools save unplanned downtime and costly repairs. By integrating with renewable energy sources like solar and wind power, these technologies ensure food processing companies maximize energy efficiency (Majeed et al., 2023b). By promoting a circular energy economy, AI-powered energy platforms contribute to a sustainable future.

### *Cold Chain Efficiency Improvements:* The cold chain is crucial in the food supply chain for maintaining the right temperatures for perishable goods during storage, shipping, and retail (Abbas et al., 2023). However, traditional refrigeration and freezing methods consume significant energy. Energy-efficient solutions are shaping cold storage systems, including phase-change cooling materials, vacuum insulation panels, solar-powered units, and AI-driven refrigeration monitoring. Real-time temperature monitoring and AI-driven developing algorithms can reduce food wastage and prevent spoilage (Bidyalakshmi et al., 2024b). AI-based smart cooling systems optimize compressor operations, fan speeds, and humidity control. Cold storage facilities can function independently of conventional power grids by integrating solar energy and battery storage, reducing dependence on fossil fuels and ensuring continuous cooling during blackouts.

### *Sustainable Food Transportation*: The food industry's carbon footprint is largely due to fuel-intensive transportation methods. Businesses are adopting hydrogen-powered freight vehicles, electric and hybrid delivery trucks, biofuel-based cargo ships, and AI-driven route optimization technology to improve sustainability and energy efficiency. AI-powered logistics solutions, real-time GPS tracking, fuel efficiency analysis, and predictive traffic modeling help determine the most energy-efficient delivery routes, reducing emissions and fuel usage (Mohsen, 2024). Last-mile food delivery is being handled by electric trucks and self-driving drones, while solar-powered refrigerated rail trains and hyperloop food transport systems are changing long-distance food logistics, enabling energy-efficient and environmentally friendly delivery of big food cargoes.

### *Energy-Efficient Food Processing and Packaging:* Food processing and packaging facilities are energy-intensive due to high-energy equipment (Szymańska & Mroczek, 2023). Low-energy methods like infrared heating, microwave-assisted drying, ultrasonic food sterilization, and cold plasma processing can reduce energy use. AI-powered smart processing systems optimize energy use and avoid overprocessing by monitoring humidity, pressure, and heat levels. AI-based automated packaging systems reduce extra packaging waste by analyzing product weight, shape, and fragility. Transitioning to biodegradable packaging reduces plastic production's energy footprint. Active packaging solutions with RFID tags and embedded sensors enable real-time food freshness monitoring, saving energy expenses. Implementing energy-efficient practices throughout the food supply chain can reduce operating expenses, environmental impact, and improve food production and distribution sustainability (D. K. Pandey & Mishra, 2024).

### ****INNOVATIONS IN FOOD SYSTEM SUSTAINABILITY****

### The global focus on sustainability in food systems is gaining momentum due to climate change, resource depletion, population growth, and food security issues. Traditional methods often lead to high waste, biodiversity loss, soil erosion, and environmental degradation. Technological advancements like blockchain, automation, AI-driven waste reduction, and smart packaging are expanding food production, processing, storage, and distribution, enhancing productivity, food quality, reducing carbon footprints, and promoting the circular economy.

### 5.1 Blockchain for Transparency and Traceability

### Blockchain technology is transforming the food supply chain by enabling complete transparency, enhancing food safety, and eliminating fraud. Traditional supply chains are frequently disjointed and hard to monitor, which makes it hard to confirm sustainability claims, ethical sourcing, and product authenticity. Real-time food product tracking is made possible by blockchain-based technologies, which provide an impenetrable digital ledger that documents each transaction from farm to fork (Sugandh et al., 2023). By enabling consumers to scan QR codes on food packaging to confirm sustainability certifications, ethical production methods, and sourcing information, this technology promotes confidence between buyers and producers (Bashir, 2022). A blockchain-based platform used by Walmart, Nestlé, and Carrefour to enhance food safety and track the origin of food products. This system has helped to reduce the time required to trace contaminated products from weeks to seconds. By guaranteeing unchangeable data records, it also stops supply chain fraud, including adulterating ingredients, mislabeling organic products, and counterfeiting high-end meals. Furthermore, by automating transactions between farmers, wholesalers, and retailers, blockchain-based smart contracts lower inefficiencies and guarantee producers receive fair prices and payments on time (Kononets et al., 2022). Figure 3 visually represents how blockchain technology improves food supply chain transparency, ensuring traceability from production to distribution.

### 

### Figure 3. Blockchain in food supply chain

### 5.2 Enhancing Food Quality with Automation

### Automation plays an important role in increasing food quality, lowering contamination risks, and assuring production uniformity (Amjad et al., 2023). Manual handling and other traditional food processing techniques raise the danger of contamination and quality variance. AI-powered robotic systems surpass human inspectors in ensuring correct, hygienic, and consistent output through the use of machine vision and deep learning algorithms (Padhiary & Kumar, 2024). Furthermore, AI-powered smart sensors in processing facilities keep an eye on variables like temperature, humidity, and air quality to guarantee that food is made in the safest possible conditions (Da Silva Ferreira et al., 2024). Large-scale food manufacturing is being improvised by autonomous robots that can do repetitive activities like chopping meat, kneading bread, and bottling beverages. This eliminates manpower dependency, boosts efficiency, and lowers supply chain waste and food recalls.

### 5.3 Waste Reduction through Technological Integration

### Almost one-third of all food produced is lost or wasted as a result of ineffective supply systems, overproduction, and inappropriate storage, making food loss a serious worldwide problem. This issue is being addressed by AI-powered waste management systems that analyze food inventories, forecast demand, and optimize distribution to cut down on surplus production (Lakhouit, 2025). In order to help food producers and merchants match supply with consumer demand and reduce overproduction and unsold food waste, AI-based demand forecasting makes use of past sales data, market trends, and climatic patterns. Furthermore, smart packaging systems with integrated freshness sensors monitor temperature, humidity, and spoiling levels in real time, alerting customers and merchants when food is about to expire and minimizing needless disposal (M. Thakur et al., 2022). By connecting food banks and charities with supermarkets, eateries, and food suppliers, IoT-enabled food donation systems make it easier to redistribute excess food to people in need rather of letting it go to waste. Additionally, a zero-waste food system is promoted by improvements in circular economy methods that allow food waste to be recycled into animal feed, biofertilizers, or anaerobic digestion to produce bioenergy (Tsegaye et al., 2021).

### FUTURE PROSPECTS IN AI AND AUTOMATION FOR FOOD SYSTEMS

### Food systems are being modified by automation, robots, and artificial intelligence (AI), which is improving food security, resource optimization, supply chain efficiency, and climate change adaption. AI and automation can speed up logistics, minimize waste, enhance food processing, and increase agricultural output. To effectively integrate these technologies, however, issues including infrastructure, cost, regulatory frameworks, and the ethical application of AI must be resolved.

### 6.1 Emerging Trends in Intelligent Food Systems

### The future of intelligent food systems will feature AI-powered autonomous farming, lab-grown proteins, automated food processing, vertical farming, blockchain-based food traceability, and individualized nutrition (Karunathilake et al., 2023; Prasad et al., 2025). These technologies will maximize agricultural yields with minimal human involvement, enabling farmers to predict weather patterns and optimize resource allocation. AI-driven meal planning algorithms and genetic dietary analysis will modify the food industry by providing personalized meals based on individual needs. Lab-grown proteins and AI-optimized substitute food sources will enhance protein intake, while vertical farming and AI-powered greenhouses will increase in urban areas. Blockchain technology will become the norm for food supply chains, ensuring safe, traceable transactions from farm to customer (Bosona & Gebresenbet, 2023). Consumers will be able to confirm ethical sourcing and environmental impact before purchasing food goods through real-time tracking of food safety parameters and carbon footprint evaluations.

### 6.2 Addressing Challenges in Technology Integration

### Agriculture might undergo a transformation thanks to AI and automation, but there are obstacles in the form of high implementation costs, limited infrastructure, farmer resistance, a lack of digital literacy, and complicated regulations (Da Silveira et al., 2023). Governments, aggrotech companies, and financial institutions must develop technology-sharing models, low-cost leasing schemes, and subsidies to guarantee accessibility. To close the digital divide, investments must be made in satellite-powered AI systems, smart agricultural apps, and rural broadband growth. Data privacy and cybersecurity issues are significant, as AI-driven food production generates sensitive data (Mehra et al., 2024). Governments must establish stringent AI ethics policies, legal frameworks for AI-driven food safety standards, lab-grown food labeling, and robotic food processing regulations.

### 6.3 Research Directions for Sustainable Food Systems

### Future AI and automation research will focus on climate-resilient crops, soil and water management, sustainable agricultural robotics, lab-grown food technologies, and AI-driven food security policy. AI-driven genetic engineering and climate modeling will develop crop types resistant to drought, pests, and nutrients (Satpathy et al., 2024). AI-based soil health monitoring systems will analyse real-time nutrient levels, pH, and organic matter composition, providing farmers with accurate fertilization and regenerative farming suggestions. AI-powered precision irrigation systems will optimize water consumption and reduce waste. Sustainable agricultural robotics will reduce energy use, environmental impact, and chemical-intensive farming (Giordano et al., 2023). AI will accelerate research into bioengineered dairy alternatives, precision fermentation, and algae-based food manufacture, reducing protein shortages and emissions.

### ****CONCLUSION****

### The integration of AI, automation, and emerging technologies is changing food systems, enhancing climate resilience, sustainability, efficiency, and food security. These advancements include precision agriculture, waste reduction, supply chain transparency, and food production optimization. AI-powered robots, machine learning, and IoT-enabled monitoring systems are improving food processing efficiency and supply chain resilience. AI-powered quality control systems are improving food safety, storage, and packaging, while blockchain technology ensures food authenticity and traceability. However, significant obstacles like high upfront costs, infrastructural constraints, digital literacy gaps, and regulatory concerns must be addressed for AI and automation to be widely adopted. Governments should invest in AI infrastructure, provide incentives for automation, and support digital literacy training for farmers. Cooperation between AI researchers, agribusinesses, and legislators is crucial for AI governance. Sustainable breakthroughs like vertical farming, solar-powered agriculture technology, lab-grown proteins, and AI-optimized water conservation are essential for reducing emissions, preserving biodiversity, and ensuring global food security. Future food systems must be inclusive, flexible, and resilient, incorporating renewable energy sources, AI-driven food production techniques, and sustainable waste reduction programs. Collaboration between governments, researchers, aggrotech entrepreneurs, and food industry leaders is crucial to ensure the ethical, fair, and effective use of automation and artificial intelligence.

### Disclaimer (Artificial intelligence)

### Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

### REFERENCES

Abbas, H., Zhao, L., Gong, X., & Faiz, N. (2023). The perishable products case to achieve sustainable food quality and safety goals implementing on-field sustainable supply chain model. *Socio-Economic Planning Sciences*, *87*, 101562. https://doi.org/10.1016/j.seps.2023.101562

Abbaspour-Gilandeh, Y., Aghabara, A., Davari, M., & Maja, J. M. (2022). Feasibility of Using Computer Vision and Artificial Intelligence Techniques in Detection of Some Apple Pests and Diseases. *Applied Sciences*, *12*(2), 906. https://doi.org/10.3390/app12020906

Alasi, S. O., Sanusi, M. S., Sunmonu, M. O., Odewole, M. M., & Adepoju, A. L. (2024). Exploring recent developments in novel technologies and AI integration for plant-based protein functionality: A review. *Journal of Agriculture and Food Research*, *15*, 101036. https://doi.org/10.1016/j.jafr.2024.101036

Aldoseri, A., Al-Khalifa, K. N., & Hamouda, A. M. (2024). AI-Powered Innovation in Digital Transformation: Key Pillars and Industry Impact. *Sustainability*, *16*(5), 1790. https://doi.org/10.3390/su16051790

Amertet, S., Gebresenbet, G., Alwan, H. M., & Vladmirovna, K. O. (2023). Assessment of Smart Mechatronics Applications in Agriculture: A Review. *Applied Sciences*, *13*(12), 7315. https://doi.org/10.3390/app13127315

Amjad, W., Munir, A., Akram, F., Parmar, A., Precoppe, M., Asghar, F., & Mahmood, F. (2023). Decentralized solar-powered cooling systems for fresh fruit and vegetables to reduce post-harvest losses in developing regions: A review. *Clean Energy*, *7*(3), 635–653. https://doi.org/10.1093/ce/zkad015

Anwar, H., Anwar, T., & Mahmood, G. (2023). Nourishing the Future: AI-Driven Optimization of Farm-to-Consumer Food Supply Chain for Enhanced Business Performance. *Innovative Computing Review*, *3*(2). https://doi.org/10.32350/icr.32.02

Arja, L. (2024). Clay 3D printed hydroponics: A paradigm to address global food insecurity. *International Journal of Architectural Computing*, *22*(4), 589–604. https://doi.org/10.1177/14780771241287826

Ashokkumar, V., Flora, G., Venkatkarthick, R., SenthilKannan, K., Kuppam, C., Mary Stephy, G., Kamyab, H., Chen, W.-H., Thomas, J., & Ngamcharussrivichai, C. (2022). Advanced technologies on the sustainable approaches for conversion of organic waste to valuable bioproducts: Emerging circular bioeconomy perspective. *Fuel*, *324*, 124313. https://doi.org/10.1016/j.fuel.2022.124313

Assimakopoulos, F., Vassilakis, C., Margaris, D., Kotis, K., & Spiliotopoulos, D. (2024). Artificial Intelligence Tools for the Agriculture Value Chain: Status and Prospects. *Electronics*, *13*(22), 4362. https://doi.org/10.3390/electronics13224362

Ayoub Shaikh, T., Rasool, T., & Rasheed Lone, F. (2022). Towards leveraging the role of machine learning and artificial intelligence in precision agriculture and smart farming. *Computers and Electronics in Agriculture*, *198*, 107119. https://doi.org/10.1016/j.compag.2022.107119

Barnavo Das, Azmirul Hoque, Suranjit Roy, Kundan Kumar, Ahad Ahmed Laskar, & Ahmed Sadique Mazumder. (2025). Post-Harvest Technologies and Automation: Al-Driven Innovations in Food Processing and Supply Chains. *International Journal of Scientific Research in Science and Technology*, *12*(1), 183–205. https://doi.org/10.32628/IJSRST25121170

Bashir, H. (2022). Leveraging technology to communicate sustainability-related product information: Evidence from the field. *Journal of Cleaner Production*, *362*, 132508. https://doi.org/10.1016/j.jclepro.2022.132508

Bazargani, K., & Deemyad, T. (2024). Automation’s Impact on Agriculture: Opportunities, Challenges, and Economic Effects. *Robotics*, *13*(2), 33. https://doi.org/10.3390/robotics13020033

Bidyalakshmi, Thingujam., Jyoti, B., Mansuri, S. M., Srivastava, A., Mohapatra, D., Kalnar, Y. B., Narsaiah, K., & Indore, N. (2024a). Application of Artificial Intelligence in Food Processing: Current Status and Future Prospects. *Food Engineering Reviews*. https://doi.org/10.1007/s12393-024-09386-2

Bidyalakshmi, Thingujam., Jyoti, B., Mansuri, S. M., Srivastava, A., Mohapatra, D., Kalnar, Y. B., Narsaiah, K., & Indore, N. (2024b). Application of Artificial Intelligence in Food Processing: Current Status and Future Prospects. *Food Engineering Reviews*. https://doi.org/10.1007/s12393-024-09386-2

Bosona, T., & Gebresenbet, G. (2023). The Role of Blockchain Technology in Promoting Traceability Systems in Agri-Food Production and Supply Chains. *Sensors*, *23*(11), 5342. https://doi.org/10.3390/s23115342

Brears, R. C. (2023). The Green Economy and the Water-Energy-Food Nexus. In R. C. Brears, *The Green Economy and the Water-Energy-Food Nexus* (pp. 31–61). Springer International Publishing. https://doi.org/10.1007/978-3-031-39679-3\_3

Caldwell, D. G. (2023). Automation in Food Manufacturing and Processing. In S. Y. Nof (Ed.), *Springer Handbook of Automation* (pp. 949–971). Springer International Publishing. https://doi.org/10.1007/978-3-030-96729-1\_44

Chakraborty, S. K., A., S., Dubey, K., Jat, D., Chandel, N. S., Potdar, R., Rao, N. R. N. V. G., & Kumar, D. (2023). Development of an optimally designed real-time automatic citrus fruit grading–sorting​ machine leveraging computer vision-based adaptive deep learning model. *Engineering Applications of Artificial Intelligence*, *120*, 105826. https://doi.org/10.1016/j.engappai.2023.105826

Chandan, A., John, M., & Potdar, V. (2023). Achieving UN SDGs in Food Supply Chain Using Blockchain Technology. *Sustainability*, *15*(3), 2109. https://doi.org/10.3390/su15032109

Chen, C., Hu, Y., Karuppiah, M., & Kumar, P. M. (2021). Artificial intelligence on economic evaluation of energy efficiency and renewable energy technologies. *Sustainable Energy Technologies and Assessments*, *47*, 101358. https://doi.org/10.1016/j.seta.2021.101358

Cheng, C., Fu, J., Su, H., & Ren, L. (2023). Recent Advancements in Agriculture Robots: Benefits and Challenges. *Machines*, *11*(1), 48. https://doi.org/10.3390/machines11010048

Chhetri, K. B. (2024). Applications of Artificial Intelligence and Machine Learning in Food Quality Control and Safety Assessment. *Food Engineering Reviews*, *16*(1), 1–21. https://doi.org/10.1007/s12393-023-09363-1

Da Silva Ferreira, M. V., Ahmed, M. W., Oliveira, M., Sarang, S., Ramsay, S., Liu, X., Malvandi, A., Lee, Y., & Kamruzzaman, M. (2024). AI-Enabled Optical Sensing for Smart and Precision Food Drying: Techniques, Applications and Future Directions. *Food Engineering Reviews*. https://doi.org/10.1007/s12393-024-09388-0

Da Silveira, F., Da Silva, S. L. C., Machado, F. M., Barbedo, J. G. A., & Amaral, F. G. (2023). Farmers’ perception of the barriers that hinder the implementation of agriculture 4.0. *Agricultural Systems*, *208*, 103656. https://doi.org/10.1016/j.agsy.2023.103656

Debnath, J., Kumar, K., Roy, K., Choudhury, R. D., & U, A. K. P. (2024). Precision Agriculture: A Review of AI Vision and Machine Learning in Soil, Water, and Conservation Practice. *International Journal for Research in Applied Science and Engineering Technology*, *12*(12), 2130–2141. https://doi.org/10.22214/ijraset.2024.66166

Dhal, S. B., & Kar, D. (2024). Transforming Agricultural Productivity with AI-Driven Forecasting: Innovations in Food Security and Supply Chain Optimization. *Forecasting*, *6*(4), 925–951. https://doi.org/10.3390/forecast6040046

Duguma, A. L., & Bai, X. (2024). How the internet of things technology improves agricultural efficiency. *Artificial Intelligence Review*, *58*(2), 63. https://doi.org/10.1007/s10462-024-11046-0

Elbasi, E., Mostafa, N., Zaki, C., AlArnaout, Z., Topcu, A. E., & Saker, L. (2024). Optimizing Agricultural Data Analysis Techniques through AI-Powered Decision-Making Processes. *Applied Sciences*, *14*(17), 8018. https://doi.org/10.3390/app14178018

Engler, N., & Krarti, M. (2021). Review of energy efficiency in controlled environment agriculture. *Renewable and Sustainable Energy Reviews*, *141*, 110786. https://doi.org/10.1016/j.rser.2021.110786

Et-taibi, B., Abid, M. R., Boufounas, E.-M., Morchid, A., Bourhnane, S., Abu Hamed, T., & Benhaddou, D. (2024). Enhancing water management in smart agriculture: A cloud and IoT-Based smart irrigation system. *Results in Engineering*, *22*, 102283. https://doi.org/10.1016/j.rineng.2024.102283

Friedman, N., & Ormiston, J. (2022). Blockchain as a sustainability-oriented innovation?: Opportunities for and resistance to Blockchain technology as a driver of sustainability in global food supply chains. *Technological Forecasting and Social Change*, *175*, 121403. https://doi.org/10.1016/j.techfore.2021.121403

Giordano, G., Murali Babu, S. P., & Mazzolai, B. (2023). Soft robotics towards sustainable development goals and climate actions. *Frontiers in Robotics and AI*, *10*, 1116005. https://doi.org/10.3389/frobt.2023.1116005

Gul, K., & Morande, S. (2024). Eliciting food waste perceptions using an AI-driven approach. *International Journal of Technology Intelligence and Planning*, *13*(3), 240–259. https://doi.org/10.1504/IJTIP.2024.140625

Gunduz, C. P. B. (2023). Eco-friendly and Cost-effective Methods Applied to Sustainable Food Industries. In E. J. Lopes, L. Q. Zepka, & M. C. Deprá, *Smart Food Industry: The Blockchain for Sustainable Engineering* (1st ed., pp. 50–71). CRC Press. https://doi.org/10.1201/9781003231059-6

Hai Alami, A., Ghani Olabi, A., Khuri, S., Aljaghoub, H., Alasad, S., Ramadan, M., & Ali Abdelkareem, M. (2024). 3D printing in the food industry: Recent progress and role in achieving sustainable development goals. *Ain Shams Engineering Journal*, *15*(2), 102386. https://doi.org/10.1016/j.asej.2023.102386

Han, Y., Du, Z., Hu, X., Li, Y., Cai, D., Fan, J., & Geng, Z. (2023). Production prediction modeling of food waste anaerobic digestion for resources saving based on SMOTE-LSTM. *Applied Energy*, *352*, 122024. https://doi.org/10.1016/j.apenergy.2023.122024

Hasan, M. M., Hossain, S., Mofijur, M., Kabir, Z., Badruddin, I. A., Yunus Khan, T. M., & Jassim, E. (2023). Harnessing Solar Power: A Review of Photovoltaic Innovations, Solar Thermal Systems, and the Dawn of Energy Storage Solutions. *Energies*, *16*(18), 6456. https://doi.org/10.3390/en16186456

Hassan, H., Ansari, F. A., Rawat, I., & Bux, F. (2025). Food Industry Waste Management: Technologies for Value Chain Addition. In A. Pandey, S. S. Suthar, & K. T.T. Amesho (Eds.), *Solid Waste Management* (pp. 3–21). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-78420-0\_1

Hoque, A., Mazumder, A. S., Roy, S., Saikia, P., & Kumar, K. (2025). Transformative Approaches to Agricultural Sustainability: Automation, Smart Greenhouses, and AI. *International Journal for Research in Applied Science and Engineering Technology*, *13*(1), 1011–1023. https://doi.org/10.22214/ijraset.2025.66494

Hoque, A., & Padhiary, M. (2024). Automation and AI in Precision Agriculture: Innovations for Enhanced Crop Management and Sustainability. *Asian Journal of Research in Computer Science*, *17*(10), 95–109. https://doi.org/10.9734/ajrcos/2024/v17i10512

Hoque, A., Padhiary, M., Prasad, G., & Kumar, K. (2025). Real-Time Data Processing in Agricultural Robotics: In D. J. Bora & R. K. Bania (Eds.), *Computer Vision Techniques for Agricultural Advancements* (pp. 431–468). IGI Global. https://doi.org/10.4018/979-8-3693-8019-2.ch014

Ibrahim, L. A., Shaghaleh, H., El-Kassar, G. M., Abu-Hashim, M., Elsadek, E. A., & Alhaj Hamoud, Y. (2023). Aquaponics: A Sustainable Path to Food Sovereignty and Enhanced Water Use Efficiency. *Water*, *15*(24), 4310. https://doi.org/10.3390/w15244310

Ikram, A., Mehmood, H., Arshad, M. T., Rasheed, A., Noreen, S., & Gnedeka, K. T. (2024). Applications of artificial intelligence (AI) in managing food quality and ensuring global food security. *CyTA - Journal of Food*, *22*(1), 2393287. https://doi.org/10.1080/19476337.2024.2393287

Jariwala, M. (2025). AI and Data Science in Sustainable Agriculture and Food Production: In M. Syafrudin, N. L. Fitriyani, & M. Anshari (Eds.), *Artificial Intelligence and Data Science for Sustainability* (pp. 123–158). IGI Global. https://doi.org/10.4018/979-8-3693-6829-9.ch005

Javaid, M., Haleem, A., Khan, I. H., & Suman, R. (2023). Understanding the potential applications of Artificial Intelligence in Agriculture Sector. *Advanced Agrochem*, *2*(1), 15–30. https://doi.org/10.1016/j.aac.2022.10.001

Jin, Y., Liu, J., Xu, Z., Yuan, S., Li, P., Wang, J., 1. Key Laboratory of Modern Agricultural Equipment and Technology, Ministry of Education, Jiangsu University, Zhenjiang 212013, China, & 2. College of Biology and the Environment, Nanjing Forestry University, Nanjing 210042, China. (2021). Development status and trend of agricultural robot technology. *International Journal of Agricultural and Biological Engineering*, *14*(3), 1–19. https://doi.org/10.25165/j.ijabe.20211404.6821

Karunathilake, E. M. B. M., Le, A. T., Heo, S., Chung, Y. S., & Mansoor, S. (2023). The Path to Smart Farming: Innovations and Opportunities in Precision Agriculture. *Agriculture*, *13*(8), 1593. https://doi.org/10.3390/agriculture13081593

Khatri, P., Kumar, P., Shakya, K. S., Kirlas, M. C., & Tiwari, K. K. (2023). Understanding the intertwined nature of rising multiple risks in modern agriculture and food system. *Environment, Development and Sustainability*, *26*(9), 24107–24150. https://doi.org/10.1007/s10668-023-03638-7

Kononets, Y., Treiblmaier, H., & Rajčániová, M. (2022). Applying blockchain-based smart contracts to eliminate unfair trading practices in the food supply chain. *International Journal of Logistics Systems and Management*, *43*(3), 297. https://doi.org/10.1504/IJLSM.2022.127082

Kumar, D., Kumar, K., Roy, P., & Rabha, G. (2024). Renewable Energy in Agriculture: Enhancing Aquaculture and Post-Harvest Technologies with Solar and AI Integration. *Asian Journal of Research in Computer Science*, *17*(12), 201–219. https://doi.org/10.9734/ajrcos/2024/v17i12539

Kumari, S., Venkatesh, V. G., Tan, F. T. C., Bharathi, S. V., Ramasubramanian, M., & Shi, Y. (2023). Application of machine learning and artificial intelligence on agriculture supply chain: A comprehensive review and future research directions. *Annals of Operations Research*. https://doi.org/10.1007/s10479-023-05556-3

Kunatsa, T. (2025). The role of artificial intelligence in greening biogas operations. In *Innovations in the Global Biogas industry* (pp. 361–397). Elsevier. https://doi.org/10.1016/B978-0-443-22372-3.00014-5

Lakhouit, A. (2025). Revolutionizing urban solid waste management with AI and IoT: A review of smart solutions for waste collection, sorting, and recycling. *Results in Engineering*, *25*, 104018. https://doi.org/10.1016/j.rineng.2025.104018

Lario, J., Mateos, J., Psarommatis, F., & Ortiz, Á. (2025). Towards Zero Defect and Zero Waste Manufacturing by Implementing Non-Destructive Inspection Technologies. *Journal of Manufacturing and Materials Processing*, *9*(2), 29. https://doi.org/10.3390/jmmp9020029

Laskar, A. A. (2024). Exploring the Role of Smart Systems in Farm Machinery for Soil Fertility and Crop Productivity. *International Journal for Research in Applied Science and Engineering Technology*, *12*(12), 2063–2075. https://doi.org/10.22214/ijraset.2024.66157

Liberty, J. T., Habanabakize, E., Adamu, P. I., & Bata, S. M. (2024). Advancing food manufacturing: Leveraging robotic solutions for enhanced quality assurance and traceability across global supply networks. *Trends in Food Science & Technology*, *153*, 104705. https://doi.org/10.1016/j.tifs.2024.104705

Majeed, Y., Khan, M. U., Waseem, M., Zahid, U., Mahmood, F., Majeed, F., Sultan, M., & Raza, A. (2023a). Renewable energy as an alternative source for energy management in agriculture. *Energy Reports*, *10*, 344–359. https://doi.org/10.1016/j.egyr.2023.06.032

Majeed, Y., Khan, M. U., Waseem, M., Zahid, U., Mahmood, F., Majeed, F., Sultan, M., & Raza, A. (2023b). Renewable energy as an alternative source for energy management in agriculture. *Energy Reports*, *10*, 344–359. https://doi.org/10.1016/j.egyr.2023.06.032

Maniruzzaman, Md., Biswas, J. C., Hossain, Md. B., Mainuddin, M., Roy, D., Yesmin, Mst. S., Kundu, P. K., & Haque, Md. M. (2025). Greenhouse gas emissions from dry season rice irrigation in Bangladesh. *Mitigation and Adaptation Strategies for Global Change*, *30*(2), 8. https://doi.org/10.1007/s11027-024-10197-3

Manoharan, G., Ashtikar, S. P., & Nivedha, M. (2024). Unveiling the Critical Role of Artificial Intelligence in Energy Management: In B. A. Riswandi, B. Singh, C. Kaunert, & K. Vig (Eds.), *Practice, Progress, and Proficiency in Sustainability* (pp. 234–253). IGI Global. https://doi.org/10.4018/979-8-3693-6567-0.ch012

Marvin, H. J. P., Bouzembrak, Y., Van Der Fels-Klerx, H. J., Kempenaar, C., Veerkamp, R., Chauhan, A., Stroosnijder, S., Top, J., Simsek-Senel, G., Vrolijk, H., Knibbe, W. J., Zhang, L., Boom, R., & Tekinerdogan, B. (2022). Digitalisation and Artificial Intelligence for sustainable food systems. *Trends in Food Science & Technology*, *120*, 344–348. https://doi.org/10.1016/j.tifs.2022.01.020

McDonald, S. D. (2024). The Impact of Data Analytics, Automation, AI, and IoT on Vietnam’s Logistics Industry. In S. D. McDonald & M. D. Kim Ngo (Eds.), *Transforming Logistics in a Developing Nation* (pp. 53–72). Springer Nature Singapore. https://doi.org/10.1007/978-981-97-7819-5\_4

Mehra, S., Rao, M., Bansal, A. V., Rathore, N., Sidana, S., Raj, S., Sinha, A., Rao, G. M., Shamim, R., Singh, N., & Kumar, B. (2024). Ethical Challenges and Innovations in AI-Driven Healthcare and Engineering: A Review of Blockchain, Cybersecurity, Data Privacy, and Knowledge Management. In P. Bhattacharya, A. Hassan, H. Liu, & B. Bhushan (Eds.), *Advances in Human and Social Aspects of Technology* (pp. 323–346). IGI Global. https://doi.org/10.4018/979-8-3693-4147-6.ch015

Michel, M., Eldridge, A. L., Hartmann, C., Klassen, P., Ingram, J., & Meijer, G. W. (2024). Benefits and challenges of food processing in the context of food systems, value chains and sustainable development goals. *Trends in Food Science & Technology*, *153*, 104703. https://doi.org/10.1016/j.tifs.2024.104703

Mishra, V., Avtar, R., Prathiba, A. P., Mishra, P. K., Tiwari, A., Sharma, S. K., Singh, C. H., Chandra Yadav, B., & Jain, K. (2023). Uncrewed Aerial Systems in Water Resource Management and Monitoring: A Review of Sensors, Applications, Software, and Issues. *Advances in Civil Engineering*, *2023*, 1–28. https://doi.org/10.1155/2023/3544724

Mohsen, B. M. (2024). AI-Driven Optimization of Urban Logistics in Smart Cities: Integrating Autonomous Vehicles and IoT for Efficient Delivery Systems. *Sustainability*, *16*(24), 11265. https://doi.org/10.3390/su162411265

Mohyuddin, G., Khan, M. A., Haseeb, A., Mahpara, S., Waseem, M., & Saleh, A. M. (2024). Evaluation of Machine Learning Approaches for Precision Farming in Smart Agriculture System: A Comprehensive Review. *IEEE Access*, *12*, 60155–60184. https://doi.org/10.1109/ACCESS.2024.3390581

Morkūnas, M., Wang, Y., & Wei, J. (2024). Role of AI and IoT in Advancing Renewable Energy Use in Agriculture. *Energies*, *17*(23), 5984. https://doi.org/10.3390/en17235984

Musa, M. K., Abdulsalam, A., Haruna, U. A., Zakariya, F., Okon, I. I., Musa, S. S., & Lucero-Prisno, D. E. (2023). Exploring the potential of artificial intelligence to boost Africa’s food security. In *Advances in Food Security and Sustainability* (Vol. 8, pp. 267–286). Elsevier. https://doi.org/10.1016/bs.af2s.2023.07.004

Olawade, D. B., Fapohunda, O., Wada, O. Z., Usman, S. O., Ige, A. O., Ajisafe, O., & Oladapo, B. I. (2024). Smart waste management: A paradigm shift enabled by artificial intelligence. *Waste Management Bulletin*, *2*(2), 244–263. https://doi.org/10.1016/j.wmb.2024.05.001

Omar, I. A., Hasan, H. R., Jayaraman, R., Salah, K., & Omar, M. (2024). Using blockchain technology to achieve sustainability in the hospitality industry by reducing food waste. *Computers & Industrial Engineering*, *197*, 110586. https://doi.org/10.1016/j.cie.2024.110586

Onyeaka, H., Tamasiga, P., Nwauzoma, U. M., Miri, T., Juliet, U. C., Nwaiwu, O., & Akinsemolu, A. A. (2023). Using Artificial Intelligence to Tackle Food Waste and Enhance the Circular Economy: Maximising Resource Efficiency and Minimising Environmental Impact: A Review. *Sustainability*, *15*(13), 10482. https://doi.org/10.3390/su151310482

Onyijen, O. H., Oyelola, S., & Ogieriakhi, O. J. (2024). Food manufacturing, processing, storage, and marketing using artificial intelligence. In *A Biologist�s Guide to Artificial Intelligence* (pp. 183–200). Elsevier. https://doi.org/10.1016/B978-0-443-24001-0.00012-9

Padhiary, M. (2023). Bridging the gap: Sustainable automation and energy efficiency in food processing. *Agricultural Engineering Today*, *47*(3), 47–50. https://doi.org/10.52151/aet2023473.1678

Padhiary, M. (2024a). Harmony under the Sun: Integrating Aquaponics with Solar-Powered Fish Farming. In *Introduction to Renewable Energy Storage and Conversion for Sustainable Development* (Vol. 1, pp. 31–58). AkiNik Publications. https://doi.org/10.22271/ed.book.2882

Padhiary, M. (2024b). The Convergence of Deep Learning, IoT, Sensors, and Farm Machinery in Agriculture: In S. G. Thandekkattu & N. R. Vajjhala (Eds.), *Designing Sustainable Internet of Things Solutions for Smart Industries* (pp. 109–142). IGI Global. https://doi.org/10.4018/979-8-3693-5498-8.ch005

Padhiary, M., Barbhuiya, J. A., Roy, D., & Roy, P. (2024). 3D printing applications in smart farming and food processing. *Smart Agricultural Technology*, *9*, 100553. https://doi.org/10.1016/j.atech.2024.100553

Padhiary, M., Hoque, A., Prasad, G., Kumar, K., & Sahu, B. (2025). Precision Agriculture and AI-Driven Resource Optimization for Sustainable Land and Resource Management: In J. A. Ruiz-Vanoye & O. Díaz-Parra (Eds.), *Smart Water Technology for Sustainable Management in Modern Cities* (pp. 197–232). IGI Global. https://doi.org/10.4018/979-8-3693-8074-1.ch009

Padhiary, M., & Kumar, R. (2024). Enhancing Agriculture Through AI Vision and Machine Learning: The Evolution of Smart Farming. In D. Thangam (Ed.), *Advancements in Intelligent Process Automation* (pp. 295–324). IGI Global. https://doi.org/10.4018/979-8-3693-5380-6.ch012

Padhiary, M., Kumar, R., & Sethi, L. N. (2024). Navigating the Future of Agriculture: A Comprehensive Review of Automatic All-Terrain Vehicles in Precision Farming. *Journal of The Institution of Engineers (India): Series A*, *105*, 767–782. https://doi.org/10.1007/s40030-024-00816-2

Padhiary, M., Roy, P., Dey, P., & Sahu, B. (2024). Harnessing AI for Automated Decision-Making in Farm Machinery and Operations: Optimizing Agriculture. In S. Hai-Jew (Ed.), *Advances in Computational Intelligence and Robotics* (pp. 249–282). IGI Global. https://doi.org/10.4018/979-8-3693-6230-3.ch008

Padhiary, M., Tikute, S. V., Saha, D., Barbhuiya, J. A., & Sethi, L. N. (2024). Development of an IOT-Based Semi-Autonomous Vehicle Sprayer. *Agricultural Research*, *13*(3). https://doi.org/10.1007/s40003-024-00760-4

Pandey, D. K., & Mishra, R. (2024). Towards sustainable agriculture: Harnessing AI for global food security. *Artificial Intelligence in Agriculture*, *12*, 72–84. https://doi.org/10.1016/j.aiia.2024.04.003

Peng, M., Liu, Y., Khan, A., Ahmed, B., Sarker, S. K., Ghadi, Y. Y., Bhatti, U. A., Al-Razgan, M., & Ali, Y. A. (2024). Crop monitoring using remote sensing land use and land change data: Comparative analysis of deep learning methods using pre-trained CNN models. *Big Data Research*, *36*, 100448. https://doi.org/10.1016/j.bdr.2024.100448

Pimenow, S., Pimenowa, O., & Prus, P. (2024). Challenges of Artificial Intelligence Development in the Context of Energy Consumption and Impact on Climate Change. *Energies*, *17*(23), 5965. https://doi.org/10.3390/en17235965

Prasad, G., Padhiary, M., Hoque, A., & Kumar, K. (2025). AI-Driven Personalized Nutrition Apps and Platforms for Enhanced Diet and Wellness: In A. M. Alhussaini Hamad & R. Soni (Eds.), *Food in the Metaverse and Web 3.0 Era* (pp. 125–158). IGI Global. https://doi.org/10.4018/979-8-3693-9025-2.ch006

Qu, J., Zhang, Z., Qin, Z., Guo, K., & Li, D. (2024). Applications of Autonomous Navigation Technologies for Unmanned Agricultural Tractors: A Review. *Machines*, *12*(4), 218. https://doi.org/10.3390/machines12040218

Rabha, G., Kumar, K., Kumar, D., & Kumar, D. (2024). A Comprehensive Review of Integrating AI and IoT in Farm Machinery: Advancements, Applications, and Sustainability. *International Journal of Research and Analytical Reviews*, *11*(4).

Rahman, M. A., Hasnain, S. M. M., Paramasivam, P., Zairov, R., & Ayanie, A. G. (2025). Solar Drying for Domestic and Industrial Applications: A Comprehensive Review of Innovations and Efficiency Enhancements. *Global Challenges*, *9*(2), 2400301. https://doi.org/10.1002/gch2.202400301

Roy, P., Sheikh, A., Kumar, D., & Saikia, P. (2025). The Convergence of Renewable Energy and Aquacultural Engineering for a Sustainable Food System. *International Journal for Research in Applied Science and Engineering Technology*, *13*(1), 844–853. https://doi.org/10.22214/ijraset.2025.66428

Satpathy, I., Nayak, A., & Poddar, S. (2024). The Transformative Potential of Artificial Intelligence (AI) in Tackling Climate Change: From Theory to Practice. In A. Bhaumik, S. Poddar, M. Dadhich, K. K. Hiran, & R. Doshi (Eds.), *Practice, Progress, and Proficiency in Sustainability* (pp. 431–448). IGI Global. https://doi.org/10.4018/979-8-3693-6522-9.ch023

Selvam, A. P., & Al-Humairi, S. N. S. (2023). *The Impact of IoT and Sensor Integration on Real-Time Weather Monitoring Systems: A Systematic Review*. In Review. https://doi.org/10.21203/rs.3.rs-3579172/v1

Shahab, H., Iqbal, M., Sohaib, A., Ullah Khan, F., & Waqas, M. (2024). IoT-based agriculture management techniques for sustainable farming: A comprehensive review. *Computers and Electronics in Agriculture*, *220*, 108851. https://doi.org/10.1016/j.compag.2024.108851

Shamsuddoha, M., & Nasir, T. (2025). Smart Practices in Modern Dairy Farming in Bangladesh: Integrating Technological Transformations for Sustainable Responsibility. *Administrative Sciences*, *15*(2), 38. https://doi.org/10.3390/admsci15020038

Shivaprakash, K. N., Swami, N., Mysorekar, S., Arora, R., Gangadharan, A., Vohra, K., Jadeyegowda, M., & Kiesecker, J. M. (2022). Potential for Artificial Intelligence (AI) and Machine Learning (ML) Applications in Biodiversity Conservation, Managing Forests, and Related Services in India. *Sustainability*, *14*(12), 7154. https://doi.org/10.3390/su14127154

Shobhana, N. (2024). AI-Powered Supply Chains Towards Greater Efficiency: In P. C. N. Figueiredo (Ed.), *Advances in Logistics, Operations, and Management Science* (pp. 229–249). IGI Global. https://doi.org/10.4018/979-8-3693-0712-0.ch011

Simane, B., Kapwata, T., Naidoo, N., Cissé, G., Wright, C. Y., & Berhane, K. (2025). Ensuring Africa’s Food Security by 2050: The Role of Population Growth, Climate-Resilient Strategies, and Putative Pathways to Resilience. *Foods*, *14*(2), 262. https://doi.org/10.3390/foods14020262

Sonowal, K. (2025). Changing Pattern of Energy Usage in North East India: A Historical Approach. In P. Singh & B. Ao (Eds.), *The Intersection of Global Energy Politics and Climate Change* (pp. 167–182). Springer Nature Singapore. https://doi.org/10.1007/978-981-96-0535-4\_7

Sugandh, U., Nigam, S., Khari, M., & Misra, S. (2023). An Approach for Risk Traceability Using Blockchain Technology for Tracking, Tracing, and Authenticating Food Products. *Information*, *14*(11), 613. https://doi.org/10.3390/info14110613

Szymańska, E. J., & Mroczek, R. (2023). Energy Intensity of Food Industry Production in Poland in the Process of Energy Transformation. *Energies*, *16*(4), 1843. https://doi.org/10.3390/en16041843

Taneja, A., Nair, G., Joshi, M., Sharma, S., Sharma, S., Jambrak, A. R., Roselló-Soto, E., Barba, F. J., Castagnini, J. M., Leksawasdi, N., & Phimolsiripol, Y. (2023). Artificial Intelligence: Implications for the Agri-Food Sector. *Agronomy*, *13*(5), 1397. https://doi.org/10.3390/agronomy13051397

Thakur, A., Venu, S., & Gurusamy, M. (2023). An extensive review on agricultural robots with a focus on their perception systems. *Computers and Electronics in Agriculture*, *212*, 108146. https://doi.org/10.1016/j.compag.2023.108146

Thakur, M., Majid, I., & Nanda, V. (2022). Smart Packaging for Managing and Monitoring Shelf Life and Food Safety. In B. N. Dar, M. A. Shah, & S. A. Mir, *Shelf Life and Food Safety* (1st ed., pp. 285–306). CRC Press. https://doi.org/10.1201/9781003091677-15

Thangamani, R., Sathya, D., Kamalam, G. K., & Lyer, G. N. (2024). AI Green Revolution: Reshaping Agriculture’s Future. In S. Balasubramanian, G. Natarajan, & P. R. Chelliah (Eds.), *Intelligent Robots and Drones for Precision Agriculture* (pp. 421–461). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-51195-0\_19

Touil, S., Richa, A., Fizir, M., Argente García, J. E., & Skarmeta Gómez, A. F. (2022). A review on smart irrigation management strategies and their effect on water savings and crop yield. *Irrigation and Drainage*, *71*(5), 1396–1416. https://doi.org/10.1002/ird.2735

Tsegaye, B., Jaiswal, S., & Jaiswal, A. K. (2021). Food Waste Biorefinery: Pathway towards Circular Bioeconomy. *Foods*, *10*(6), 1174. https://doi.org/10.3390/foods10061174

Usigbe, M. J., Asem-Hiablie, S., Uyeh, D. D., Iyiola, O., Park, T., & Mallipeddi, R. (2023). Enhancing resilience in agricultural production systems with AI-based technologies. *Environment, Development and Sustainability*, *26*(9), 21955–21983. https://doi.org/10.1007/s10668-023-03588-0

Vegesna, V. V., Prabhakaran, S. M., & Whig, P. (2024). AI for Food Safety: Leveraging Artificial Intelligence to Ensure a Safe and Reliable Food Supply. In S. Patnaik, A. M. Hamad, D. Paul, P. K. Dutta, & M. Shafiq (Eds.), *Advances in Medical Diagnosis, Treatment, and Care* (pp. 501–524). IGI Global. https://doi.org/10.4018/979-8-3693-5528-2.ch019

Verma, S., Mishra, S., Chowdhury, S., Gaur, A., Mohapatra, S., Soni, A., & Verma, P. (2021). Solar PV powered water pumping system – A review. *Materials Today: Proceedings*, *46*, 5601–5606. https://doi.org/10.1016/j.matpr.2020.09.434

Vlăduț, N.-V., & Ungureanu, N. (2024). Beyond Agriculture 4.0: Design and Development of Modern Agricultural Machines and Production Systems. *Agriculture*, *14*(7), 991. https://doi.org/10.3390/agriculture14070991

Waseem, M., Raza, A., & Malik, A. (2024). AI-Driven Crop Yield Prediction and Disease Detection in Agroecosystems: In B. Singh, C. Kaunert, K. Vig, & S. Dutta (Eds.), *Practice, Progress, and Proficiency in Sustainability* (pp. 229–258). IGI Global. https://doi.org/10.4018/979-8-3693-6336-2.ch009

Zahoor, I., Ahmad Wani, S., & Ganaie, T. A. (2024). *Artificial Intelligence in the Food Industry: Enhancing Quality and Safety* (1st ed.). CRC Press. https://doi.org/10.1201/9781032633602

Zamnuri, M. A. H. B., Qiu, S., Rizalmy, M. A. A. B., He, W., Yusoff, S., Roeroe, K. A., Du, J., & Loh, K.-H. (2024). Integration of IoT in Small-Scale Aquaponics to Enhance Efficiency and Profitability: A Systematic Review. *Animals*, *14*(17), 2555. https://doi.org/10.3390/ani14172555

Zatsu, V., Shine, A. E., Tharakan, J. M., Peter, D., Ranganathan, T. V., Alotaibi, S. S., Mugabi, R., Muhsinah, A. B., Waseem, M., & Nayik, G. A. (2024). Revolutionizing the food industry: The transformative power of artificial intelligence-a review. *Food Chemistry: X*, *24*, 101867. https://doi.org/10.1016/j.fochx.2024.101867

Zhao, H., Di, L., Guo, L., Zhang, C., & Lin, L. (2023). An Automated Data-Driven Irrigation Scheduling Approach Using Model Simulated Soil Moisture and Evapotranspiration. *Sustainability*, *15*(17), 12908. https://doi.org/10.3390/su151712908

Zhou, Y. (2022). Low-carbon transition in smart city with sustainable airport energy ecosystems and hydrogen-based renewable-grid-storage-flexibility. *Energy Reviews*, *1*(1), 100001. https://doi.org/10.1016/j.enrev.2022.100001