International Journal of Computer Applications Technology and Research
Volume 14–Issue 03, 140 – 146, 2025, ISSN:-2319–8656
DOI:10.7753/IJCATR1403.1013

AI for Post-Harvest Loss Reduction and Food Security in the US

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Abstract: Post-harvest losses in the United States are a significant challenge to food availability, economic viability, and agricultural sustainability, and bear implications that extend to both the incomes of farmers and national food security. In this study, we examine how Artificial Intelligence (AI) technologies can be used to mitigate them and reinforce food security in the agricultural environment of the United States. Conducting analysis of post-harvest loss trends over the entire food supply chain, in the specific form of losses in the course of storage in buildings, transportation infrastructure, and processing facilities, this study highlights the necessity of the application of technology in post-harvest loss prevention. Examining varied applications of AI in post-harvest management, including predictive modeling for forecasting deterioration and storage maximizing, quality assessment system-enhancing using Artificial Intelligence for classifying fresh produce, and intelligent supply chain management for logistics optimization and delivery time minimization, this study estimates the impact of these available AI solutions on food security by analyzing improved accessibility of food, economic benefits to stakeholders, and environmental gains in the form of waste reduction and resource optimization. Considering also the challenges of deployment in the form of technology, funding, and knowledge gaps, as well as ethical implications of workforce displacement and data protection concerns, this study also looks for innovative developments in AI and public policies in support of AI in agriculture in the United States. The paper concludes by providing a synoptic view of the revolutionizing impact of AI in minimizing post-harvest losses and enhancing food security in the United States in providing implementable strategies and pointing toward vital directions for further study and techno-developments.

Keywords: Post harvest losses; Artificial Intelligience; style; Food security, Supply Chain Optimisation,Sustainable Agriculture

1. Introduction

The agricultural industry in the United States is a pillar of the The agricultural industry in the United States is a pillar of the national economy and well-being, both as a primary provider of sustenance and key creator of employment opportunities [35][24]. Despite overall growth in agricultural technologies, significant amounts of food are lost or spoilt in post-harvest phases, posing significant threats to both food safety and economic viability [33][32]. These post-harvest losses are observed along the course of the journey of the supply chain of the food, from initial farm gathering to end-consumer use, involving essential stages of product handling, warehousing, manufacturing, distribution through logistics, and retail stocking [44][54].The implications of post-harvest losses are extensive across various aspects. Economically, the losses constitute a significant wastage of resources that were invested in workforce labor, use of electricity, water, and utilization of agricultural land in growing food that never gets consumed [7][54]. Not only does wastage of this nature diminish agricultural stakeholders' potential revenue, it also increases the cost of food for consumers [32]. Socially, post-harvest losses exacerbate food insecurity issues, subjecting marginalized groups of people to difficulties in accessing proper nutritional resources [43].

Environmentally, spoiled uneaten food in waste centers emits greenhouse gases, while the wasted resources in production raise the environmental footprint of the food system [33].

Despite the existence of well-developed agricultural infrastructure in the United States, there are post-harvest losses that it continues to encounter. Inefficiencies in transport, processing, and storage account significantly for food wastage ahead of the consumers [22][7]. Management of post-harvest loses is crucial in order to increase the resilience of the food system in the US, ensure fair and sustainable distribution of the food, and minimize the environmental impact of wastage [27].In solving the problem of minimizing loss post-harvest and enhancing the food security of the United States of America, this paper examines the innovative potential of Artificial Intelligence (AI) technologies in solving it. Having a higher capacity to handle large amounts of data, identify complex patterns, and make smart decisions, AI holds the potential to improve every facet of the post-harvest supply chain [43][55]. Through in-depth examination of state-of-the-art literature and Artificial Intelligence innovative applications in predictive modeling, quality analysis, and supply chain optimization, this paper seeks to show how these technologies can be applied in solving minimization of waste in the post-harvest supply of food, quality of the crops and safety, and in establishing a stronger and equitable post-harvest distribution system in the nation [50].Additionally, this analysis will examine the impediments and opportunities surrounding the application of AI in the agriculture sector in America, addressing ethical, societal, economical, and technical concerns and proffering strategic recommendations for studies and policy platforms for full incorporation of AI in ensuring enhanced food security and sustainability.

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2. Global Food Security and Post-Harvest Losses

Food security is a holistic concept which extends to beyond the availability of food. For the Food and Agriculture Organization of the United Nations (FAO), food security involves a state where each individual has consistent physical, social, and economic access to ample, safe, and nutritious food to ensure their dietary requirements and food preferences for a healthy active life [8]. It is a comprehensive definition that encompasses four basic components: availability, accessibility, utilization, and stability [14].

Availability involves the presence of food resources in physical terms, obtained either by domestic production, imports from abroad, or through humanitarian aid [28]. Having enough quantities of food in a given territory is the overall underpinning of food security.

Accessibility concerns people's ability to acquire food by both economic means and access in the physical sense [14]. Even if food is available, people need to have adequate resources to afford it and feasible means to access places of distribution.

Utilization focuses on the quality and safety of the food, together with the capacity of individuals to properly consume and digest their dietary intake. It involves nutritional quality, proper methods of food preparation, and proper sanitation procedures to avert associated illnesses [8].

Stability involves the temporal aspect of food security, where there is a consistent availability, accessibility, and utilization of resources of food over a long-term perspective. Food systems need to exhibit resistance to various disruptive factors, such as economic variability, climate-related disasters, and market volatility, to show consistent food security among populations [9].

The importance of attaining food security transcends several spheres. It is a pillar of health and well-being of the population, providing the nutrients needed for proper physical development and mental functioning while avoiding nutritional deficiency and related complications [32]. Secondly, attainment of food security also ensures economic stability, as well-nourished populations are characterized by improved productivity and diminished susceptibility to health-instigated problems. It also ensures social harmony by alleviating hunger and poverty, which tend to be breeding grounds for social strife and violence. In today's world of growing populations and increasing environmental demands, attaining food security is a key aspect of sustainable development and a basic requirement for social progression.

3.0 Post-Harvest Losses in the US

Post-harvest loss in the United States accounts for a significant portion of agricultural production during the whole process of harvesting to the point of consumption by consumers [54]. While detailed quantification in various commodities and methods of estimation may vary, conclusions in research always point to heavy loss of food in various phases of the post-harvest supply chain [15]. Post-harvest loss is the outcome of many related causes of inefficiency in the post-harvest, transport, and processing systems.

3.1 Storage Inefficiencies

Suboptimal and outdated storehouses are one of the main causes of post-harvest losses in the United States [22]. Without proper temperature and humidity controls, foods tend to deteriorate, spoil, or microbially spoil. Pests like rodents and insects also cause extensive damage to stored farm commodities [45]. Poor performance of air flow systems and suboptimal sanitation processes in storehouses are the causes of these issues, resulting in extensive quantitative and qualitative losses [7].

3.2 Transportation Inefficiencies

Transport of agricultural products across the wide geographical scope of the United States results in immense losses. Its delays owe mainly to logistical complexity and shortage of infrastructure and result in greater damage to perishables. Physical damage of the commodities during handling processes in the form of bruising and crushing results in making the products unsafe for delivery to markets [34]. As well as that, lack of correct temperature control of refrigerated vehicles enhances spoilage issues mainly in temperature-sensitive commodities like dairy products, meat, and vegetables and fruits [25].

3.3 Processing Inefficiencies

At various stages of the processing chain, ranging from the preparation of the agricultural product to the packaging of the final consumer, losses occur [51]. Inefficient processing equipment lead to physical degeneration of the product and material loss [40]. Excessive processing steps or improper procedures lead to the loss of nutritional value and quality of the product, which affects consumer demand [43]. In addition, improper quality control procedures during processing activities fail to identify and remove defective or contaminated products, resulting in a ripple of losses in the supply chain [37].

These system inefficiencies in the post-harvest supply chain across the United States also reduce aggregated availability of the food and generate significant economic and environmental consequences, stressing the need to enforce proper loss-reduction strategies [54].

4.AI Applications in Post-Harvest Management

Artificial Intelligence (AI) provides a wide range of innovative tools and methods for use across the whole post-harvest supply chain of food to tackle inefficiency and loss. Through infusing data analysis methods with machine learning algorithms, computer vision technology, and other tools of Artificial Intelligence, organizations are able to optimize processes better, increase decision-making capabilities, and further increase food security mechanisms [18][5].

4.1 Predictive Analytics

Predictive analytics is a state-of-the-art branch of AI that utilises historical data and complex statistical methods to forecast upcoming scenarios [42]. In post-harvest management systems, these analytical abilities can accurately forecast upcoming spoilage of stored agricultural crops by analyzing critical parameters like environmental temperature, humidity levels, storage days, and initial states of the crops [38][30]. Through holistic analysis of sensor data of the storage facilities, AI programs efficiently identify recurring patterns and anomalies that reflect upcoming deterioration threats, enabling them to implement counter-measures in a timely fashion.

4.1.1 Spoilage Forecasting

Advanced AI models may be calibrated using extensive historical data on the conditions of the storage and corresponding patterns of deterioration in various agricultural commodities. Advanced models enable exact predictions of the viability of surviving products under prevailing conditions [51]. These capabilities enable stakeholders to make well-informed decisions on logistics scheduling, inventory management, and application of the necessary precautions to maintain the products [36].

4.1.2 Optimising Storage Conditions

Real-time analysis of environmental parameters by AI-enabled monitoring systems, such as variations in temperature, humidity, and other storehouse parameters, is used to identify ideal preservation conditions for ensuring quality maintenance and extending shelf life [30]. Based on continuous monitoring and comparison of parameters with ideal commodity parameters, the AI algorithms independently adjust the air supply systems, temperature, and water levels to set-up environments that reduce spoilage while increasing storage life [6].

Incorporating predictive analytics in the management of storage showcases considerable potential for diminished losses of perishable products, improved product quality, and better economic benefits to agricultural producers and storage facility owners [1][38].

4.1.3 Quality Control

Quality maintenance throughout the post-harvest supply chain remains crucial for meeting consumer expectations and minimizing losses [23]. Advanced AI-powered computer vision technologies provide efficient automated solutions for sorting and grading fruits and vegetables based on multiple quality indicators, including dimensional characteristics, morphology, pigmentation, and defect identification [56][41].

Automated Sorting: AI algorithms can be trained to analyse images of fruits and vegetables produce analyzed by sophisticated imaging systems on automated sorting lines. These advanced algorithms effectively classify and sort items according to established parameters, including dimensional specifications and morphological standards for various market classifications [53]. Modern automated sorting technologies demonstrate superior processing capabilities, handling substantial produce volumes with enhanced precision and reliability compared to traditional manual sorting approaches [16].

4.1.4 Defect Detection and Grading

Advanced machine learning models are designed to identify fruit and vegetable surface blemishes of various kinds, including bruising, skin damage, cuts, and disease-caused or decomposing deterioration marks [56]. Through in-depth image analysis, computer vision-based systems economically sort and remove degraded materials during the sorting process, ensuring that high-quality produce is carried forward through grading and distribution channels [41]. Because of the capabilities of the AI system, exact grading by defect category and severity is also facilitated, paving the way for strategic diversion of minimally degraded products to secondary markets or processing facilities, thus maximizing resource utilization [20].

The application of AI sorters and graders gives significant quality consistency and accuracy benefits as well as reduces operating costs, reduces defective product distribution, and maximizes harvested crops' utilization [3][23].

4.3 Supply Chain Optimization

Streamlining logistics for minimized transit duration and reduced spoilage.Efficient agricultural product transportation from production sites to end consumers remains essential for optimizing delivery times and minimizing spoilage risks, especially for highly perishable items [52]. AI-driven solutions demonstrate significant potential in enhancing multiple aspects of food supply chain logistics [21][13].

4.1.5 Route Optimisation

Advanced AI technologies operate on real-time data of traffic trends, weather conditions, transport infrastructure, and delivery schedule to establish the best course of transportation [57]. Through dynamic route realignment according to changing conditions, AI systems efficiently minimize transit length, maximize the use of fuels, and provide improved freshness of perishables [21].

Predictive Logistics: Advanced AI systems demonstrate remarkable capabilities in anticipating potential supply chain disruptions, including weather-related delays, transportation bottlenecks, and infrastructural challenges [42]. This predictive capacity enables supply chain stakeholders to implement proactive adjustments to logistics strategies, establish alternative routing protocols, and deploy preventive measures to maintain consistent produce delivery schedules while preserving product quality standards [10].

4.1.6 Inventory Management and Demand Forecasting

Sophisticated analytical platforms equipped with AI can accurately handle extensive datasets, comprising sales histories, seasonal variations, and market indicators, to accurately predict demand for various agricultural products. Advanced forecasting allows for precise inventory control systems to ensure that products are made available in optimal amounts in distribution channels while keeping excess inventory buildup and related spoilage risk to a bare minimum [36].

The application of logistics optimization platforms that leverage AI drives improved supply chain efficiency, agility, and robustness, leading to faster delivery cycles, less product spoilage, and overall increased consistency of distribution of high-quality products to end customers [13].

5. Impact on Food Security

The strategic integration of Artificial Intelligence (AI) across post-harvest management operations within the United States demonstrates substantial potential for strengthening national food security through multiple interconnected mechanisms.

5.1 Increased Availability

The key value that AI deployment brings to US food security is evident in its proven capacity to reduce post-harvest losses and waste [35]. Through predictive analytics in the optimization of store environments, AI technologies reliably prolong product lifespan and spoilage events while in store, keeping larger amounts of harvested crops in edible condition [22]. AI-improved quality evaluation systems in the course of sorting and grading successfully salvage edible products that might previously be rejected by conventional methods in favor of cosmetic blemishes, thus pushing additional amounts of saleable crops [56]. Further, AI-optimized supply chain logistics experience considerable gains in transit time and transport-induced deterioration, keeping product quality superior during the distribution process [52]. Cumulatively, the total of these loss reduction methods across post-harvest processes significantly raises the availability of food in the national distribution system, explicitly improving food security by providing ample supply to meet population demands [33].

5.2 Economic Benefits

Post-harvest management using AI-based solutions yields significant economic benefits for agricultural actors across the US food supply chain [43]. For farm growers, the capacity to reduce product degradation during storing phases and optimize handling-caused losses means that a greater percentage of harvested crops arrive in market fit, directly maximizing revenue generation capacity and operating profitability margins [7]. Automation of traditionally manual activities such as the sorting of produce and quality grading using AI-based automation systems minimizes labor-related charges while maximizing overall operating efficiency performance [16]. Logistics capacity that is AI-enabled counters transportation-related charges, maximizes the usage of fuels per usage cycle, and streamlines the inventory manageability operation, providing significant cost savings to distribution partners, processing centers, and store outlets [13]. These cumulative cost benefits fortify the economic viability of agricultural undertakings while enabling less volatile consumer prices by lessening supply volatility caused by post-harvest losses [32].

5.3 Environmental Considerations: Minimizing waste and resource use

The use of AI technologies that reduce post-harvest loss results in important environmental gains through waste minimization and increased efficiency in utilising resources in US agricultural systems [27]. Efficient storage and handling practices reduce waste accumulation in landfill facilities, which leads to lower greenhouse gas emissions produced by decomposition [33]. Precise agriculture practices that rely on AI minimize the use of necessary resources such as water, fertilizers, and protection chemicals, hence decreasing the environmental impact of agriculture [50]. Artificial intelligence-assisted logistics networks make sweeping reductions in the fuels consumed in transportation, further decreasing the carbon footprint of distribution processes [57]. Through end-to-end minimisation of waste, AI technology ensures the attainment of sustainable food systems that conserve natural resources, mitigate environmental degradation, and complement overall national and global sustainability objectives [54].

6.0. Challenges and Future Prospects

Although AI technologies exhibit immense potential in checking post-harvest losses and enhancing food security in the United States, several challenges need to be focused on in ensuring successful large-scale application.

Adoption Barriers:Technological, economic, and educational challenges

The application of AI solutions in post-harvest management of the agricultural sector in the US is faced by various technological, economic, and educational barriers, especially for small and medium-scale agricultural businesses [39].

6.2 Technological Barriers: The application of AI solutions requires strong digital infrastructure and connectivity, which continues to be uneven in agricultural farm regions [19]. Integrating AI platforms with traditional farm machinery and post-harvest processing equipment poses serious technical hurdles and system interoperability issues [49]. Moreover, protection of the large amounts of data harvested by means of AI-driven systems requires strict cybersecurity standards in order to maintain data integrity and safeguard it [2].

6.3 Economic Barriers: The high initial investment in the components of AI systems, which involve specialized sensors, imaging technologies, and robotic implementations, pose cost barriers to agricultural operators [11]. Establishing tangible returns on investment in the technologies tends to be difficult, especially when the focus is on long-term economic value addition and incentives for adoption [47]. Maintenance and data infrastructure-related recurring costs for system maintenance, software updates, and data management infrastructure also affect the profitability of strategies for implementing AI.

6.4 Educational Barriers: Limited digital skills and lack of awareness of the capabilities of AI among agricultural actors frequently lead to resistance to adoption [46]. Agricultural labor often does not possess the specialized technical skills needed to operate and interpret AI-based systems properly [4]. Closing the knowledge gaps using deep training programs and agricultural extension programs is essential in the maximisation of the use of AI in post-harvest management [31].

7. Ethical And Social Implications

The progressive integration of AI technologies within the US post-harvest agricultural sector introduces significant ethical and social considerations requiring thorough examination [48].

7.1 Employment Impacts

The adoption of AI-driven robotic harvesting systems has important implications for agricultural labor displacement [29]. Although the technologies increase working efficiency and lower operating costs, it is essential that the social impact of job decline be managed, particularly in the rural sector where agricultural labor is the predominant source of income. It requires the design of extensive retraining programs, establishment of technologically centered agricultural jobs, and the putting in place of supportive policies for dispossessed workers [26]. Enabling a smooth transition that takes seriously both employment stability and livelihood sustainability is the key to the successful incorporation of AI in agriculture.

7.2 Data Privacy Concerns

Post-harvest management involves significant data collection and analysis, including farm productivity parameters in detail, store environment data, and supply chain operation data [2]. Data protection issues and property rights arise, as sensitive agronomic information is exposed to unauthorized access or misuse [48]. It is important to introduce in-depth policies and structures that ensure data collection, storing procedures, and sharing practices in the context of agronomic data to protect the privacy of the growers and build the confidence of the stakeholders in using the AI-driven systems [48]. Transparency in using and interpreting the data by the algorithms is also important to ensure accountability and build confidence among farm communities.

Effectively addressing these social and ethical implications through comprehensive policymaking, inclusive stakeholder participation, and careful deployment of AI becomes critical in ensuring that there are equitable and social gains in the US agricultural economy.

8. Conclusion

Artificial Intelligence (AI) holds immense potential to revolutionize post-harvest management in the United States, providing creative solutions to the chronic issue of food loss and waste. Utilizing predictive analytics, AI optimizes forecasting of the deterioration of produce and optimization of storage conditions, greatly enhancing the length of time harvested crops remain in freshness [38][30]. AI-assisted quality control processes ensure that precise sorting and grading are carried out, resulting in superior quality of the produce while keeping distribution of inferior quality food products to consumers to a bare minimum [23][56]. Integration of AI in supply chain functions reduces complexity in logistics, saves transportation time, and maximizes inventory control, all of which add to a more efficient waste-minimizing infrastructure of food distribution [52][57].

The deployment of these solutions using AI provides various benefits to the food security in the US. Reduction of post-harvest losses directly makes the overall supply chain of the food system stronger, allowing greater availability of healthy food products to various segments of the population [33][35]. Economically, deployment of AI provides significant cost savings opportunities to agricultural actors by ensuring greater productive capability in operations, reduced labor costs, and less generation of waste [43][7]. On the environmental front, AI-driven efficiencies in storage, transportation, and resource utilization contribute to lowering greenhouse gas emissions and conserving natural resources, aligning with broader sustainability goals [27][54].

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