Advances in Post-Harvest Technology for Reducing Food Loss: A Socio-Technical Systems Perspective

Oisín Murphy
Department of Soil and Water Sciences, University of Florida
omurphy@ufl.edu

Thandeka Mpofu
Department of Food Science and Nutrition, University of Minnesota Twin Cities
tmpofu@umn.edu

Giacomo Moretti
Department of Viticulture and Enology, California State University, Fresno
gmoretti@csufresno.edu

Abstract

Post-harvest food loss represents one of the most significant inefficiencies in the global agricultural system, undermining food security, economic stability, and environmental sustainability. While much of the historical focus in agricultural research has been placed on increasing primary production and yields, the structural failures occurring between the farm gate and the retail market result in the loss of nearly one-third of all food produced globally. This research paper examines the recent technological and systemic advances in post-harvest management through an interdisciplinary lens, integrating engineering, artificial intelligence, and socio-technical infrastructure analysis. We explore the transition from passive storage methods to active, intelligent, and data-driven preservation systems. Central to this discussion is the deployment of decentralized cold chains, the integration of Internet of Things (IoT) sensors for real-time monitoring, and the use of machine learning for predictive logistics. The paper argues that reducing food loss is not merely a technical challenge of better refrigeration or packaging, but a systemic problem involving infrastructure robustness, governance, and distributive fairness. By analyzing the trade-offs between centralized industrial efficiency and decentralized resilience, we identify the necessary policy interventions and architectural shifts required to modernize global food networks. We conclude that a holistic, generative approach to post-harvest technology—one that treats food loss as a symptom of broader systemic misalignment—is essential for achieving long-term global food security in an era of climatic volatility and population growth.

Keywords:
Post-Harvest Technology, Food Loss Mitigation, Socio-Technical Infrastructure, Cold Chain Logistics, Agricultural Engineering, Artificial Intelligence, Systemic Resilience.

1. Introduction

The global agricultural landscape is currently characterized by a profound paradox: while technological advancements have allowed for unprecedented levels of food production, the mechanisms for preserving and distributing that bounty remain dangerously underdeveloped or structurally flawed. This inefficiency is most visible in the phenomenon of post-harvest loss, which refers to the quantitative and qualitative degradation of agricultural products as they move through the supply chain. Unlike food waste, which predominantly occurs at the retail and consumer levels in high-income countries, food loss is a systemic failure concentrated in the stages of harvesting, handling, storage, and transport. The scale of this loss is staggering, with profound implications for the global economy and the ecological health of the planet. Every ton of food lost represents not only a missed opportunity to alleviate hunger but also a wasted investment of land, water, energy, and labor, coupled with the unnecessary emission of greenhouse gases.

Historically, post-harvest technology was viewed as a secondary concern, subordinate to the primary goal of increasing crop yields. However, as the limitations of land expansion and intensive chemical inputs become more apparent, the focus of researchers and policymakers has shifted toward the optimization of existing resources. Modernizing post-harvest systems requires more than just incremental improvements in hardware; it necessitates a fundamental rethinking of how food moves through time and space. This involves the application of large-scale systems engineering to create infrastructures that are both robust against shocks and sensitive to the biological requirements of the products they carry. The transition toward a "loss-aware" food system involves the integration of advanced sensors, autonomous logistics, and regenerative energy sources into a cohesive socio-technical architecture.

This paper provides a comprehensive analysis of the technological frontiers in post-harvest management. We move beyond the traditional siloed approach of agricultural science to incorporate insights from systems engineering and artificial intelligence. By examining the structural trade-offs inherent in different technological pathways, we aim to provide a roadmap for the deployment of solutions that are not only technically viable but also socially equitable and environmentally sustainable. The following sections will detail the biological and mechanical stressors that drive loss, the digital and physical infrastructures that mitigate it, and the governance frameworks necessary to ensure that these advances benefit the most vulnerable actors in the global food network.

2. Biological Constraints and Mechanical Stressors in Post-Harvest Physiology

The engineering of post-harvest systems must begin with a deep understanding of the biological nature of the "cargo" itself. Unlike manufactured goods, agricultural products remain living organisms after harvest, continuing to respire and respond to their environment. This physiological activity is the primary driver of senescence and decay. The rate of respiration is highly dependent on temperature, humidity, and the gaseous composition of the surrounding atmosphere. From a systems perspective, the post-harvest chain must be viewed as a mobile life-support system that seeks to slow down the biological clock of the product without inducing chilling injury or anaerobic fermentation. This requirement creates a narrow operational window for engineering interventions.

Mechanical stressors during harvesting and handling introduce physical damage that serves as an entry point for pathogens. In many regions, the lack of specialized harvesting machinery or standardized containers leads to bruising and skin breaks that drastically reduce the shelf life of produce. The trade-off between the speed of mechanized harvesting and the delicacy of manual labor is a central theme in post-harvest engineering. Advanced robotics, equipped with soft-touch end-effectors and computer vision, are beginning to bridge this gap, allowing for high-throughput harvesting that maintains the physical integrity of the crop. However, the deployment of such technology is often limited by the lack of infrastructural support and the high capital expenditure required for entry.

Furthermore, the interaction between biological pathogens and the storage environment represents a complex ecological problem. Mycotoxin contamination in stored grains, for instance, is a major source of loss that has direct implications for human health. Engineering solutions such as hermetic storage and modified atmosphere packaging (MAP) aim to create environments that are lethal to pests and fungi while preserving the nutritional quality of the food. The success of these technologies depends on the integrity of the containment systems and the ability to maintain precise atmospheric conditions over long distances. Understanding these biological and mechanical variables is essential for designing the sensors and control systems that form the backbone of modern post-harvest infrastructure.

3. The Socio-Technical Architecture of the Cold Chain

The cold chain is arguably the most critical piece of infrastructure in the fight against food loss. It consists of a seamless series of temperature-controlled storage and distribution activities that maintain the "cold path" from the farm to the consumer. In many developing regions, the "missing middle" of the supply chain—the lack of refrigerated transport and localized pre-cooling facilities—is the primary cause of post-harvest loss. Building a robust cold chain is not merely a task of installing refrigerators; it is a socio-technical challenge that involves the coordination of energy grids, transport networks, and human expertise.

The architecture of a sustainable cold chain must address the "energy-food-nexus." Traditional refrigeration relies on carbon-intensive energy and high-global-warming-potential refrigerants, creating a conflict between food security goals and climate targets. Advances in post-harvest technology are therefore increasingly focused on decentralized, renewable-energy-powered cooling solutions. Solar-powered cold rooms and phase-change material (PCM) storage units allow for localized cooling in areas with unreliable power grids. These modular systems provide a buffer against the volatility of the energy supply, ensuring that the biological integrity of the produce is maintained even during power outages. From a systems engineering standpoint, the integration of these decentralized nodes into the larger global grid requires sophisticated management software that can balance local energy availability with global demand signals.

The governance of the cold chain also presents significant challenges regarding fairness and access. In highly centralized systems, the benefits of cold chain infrastructure often accrue to large-scale commercial producers, while smallholders are excluded due to the high costs of participation. A more equitable architecture would favor "community cooling hubs" or "cooling-as-a-service" (CaaS) models, where farmers pay only for the volume of food they store rather than owning the equipment. This shift from an asset-heavy to a service-oriented model can democratize access to preservation technology, reducing loss among the world's most vulnerable producers. Policy frameworks must support these innovative business models by providing low-interest financing for community-owned infrastructure and establishing standards for interoperability between different logistical providers.

4. IoT and Real-Time Monitoring: The Digital Nervous System

The integration of the Internet of Things (IoT) into post-harvest systems has transformed the supply chain from a "black box" into a transparent, data-rich environment. IoT sensors can monitor a wide range of variables, including temperature, relative humidity, ethylene levels, and CO2 concentrations, providing a continuous stream of data about the health of the product. This digital nervous system allows for the transition from reactive to proactive management. When a sensor detects a temperature excursion in a shipping container, automated alerts can trigger immediate corrective actions, such as adjusting the refrigeration unit or rerouting the shipment to a closer market to avoid total loss.

The deployment of IoT at scale introduces significant engineering challenges related to data architecture and robustness. Sensors must be low-cost, durable, and capable of operating in harsh agricultural environments with minimal maintenance. Furthermore, the massive volume of data generated by these devices requires edge computing capabilities—processing data locally on the device or at the warehouse level rather than sending everything to a centralized cloud. This reduces latency and ensures that critical decisions can be made even in areas with limited internet connectivity. The robustness of the digital layer is just as important as the physical layer; if the sensors fail or the data is compromised, the entire preservation system becomes blind.

Traceability is another critical benefit of IoT integration. By linking sensor data with blockchain or other distributed ledger technologies, stakeholders can create an immutable record of a product's journey. This transparency is essential for food safety and for verifying the sustainability claims of producers. For instance, a shipment of organic fruit can be "audited" to ensure it never left the required temperature range or was never exposed to certain chemicals during transport. From a governance perspective, this level of traceability can facilitate better regulatory oversight and provide consumers with the information they need to make ethically and environmentally informed choices. The challenge lies in creating global standards for data sharing that protect the privacy and commercial interests of all parties involved while still providing the necessary transparency.

5. Artificial Intelligence and Predictive Logistics

While IoT provides the data, artificial intelligence (AI) provides the "intelligence" to interpret and act upon that data. Machine learning algorithms can analyze historical patterns and real-time sensor inputs to predict the remaining shelf life of a product with high accuracy. This capability is a game-changer for logistics management. Instead of the traditional "first-in, first-out" (FIFO) inventory system, AI enables a "first-expired, first-out" (FEFO) approach. By dynamically adjusting the distribution priority based on the actual condition of the produce rather than arbitrary date labels, retailers and distributors can significantly reduce the amount of food that spoils before it reaches the shelf.

AI also plays a crucial role in optimizing the routing and scheduling of food shipments. Predictive models can account for weather patterns, traffic congestion, and the operational status of ports to identify the most efficient paths for perishable goods. In the event of a disruption—such as a port strike or a major storm—AI systems can simulate thousands of alternative scenarios in seconds, allowing for a rapid and resilient response. This "algorithmic resilience" is essential for managing the complexity of modern, globally integrated food networks. However, the reliance on AI also introduces risks, particularly regarding algorithmic bias and the concentration of data power. If the models are trained only on data from large industrial farms, they may not accurately reflect the needs or conditions of small-scale producers in the Global South.

The integration of AI into post-harvest systems must also consider the human-in-the-loop. Technology should augment, not replace, the expertise of agricultural professionals. User interfaces for AI-driven logistics must be intuitive and accessible to workers with varying levels of technical literacy. Furthermore, the deployment of AI requires a robust legal framework to address issues of liability and accountability. If an autonomous routing system makes a decision that leads to a catastrophic loss of food, it must be clear who is responsible. Developing "explainable AI" that provides the reasoning behind its recommendations is a key research priority for ensuring the trustworthiness and social acceptance of these technologies.

6. Structural Trade-offs: Centralization versus Decentralization

A central tension in the engineering of post-harvest systems is the trade-off between centralized efficiency and decentralized resilience. The industrial model of the last century favored massive, centralized processing and storage facilities that achieved significant economies of scale. These facilities can afford the most advanced preservation technologies and can process enormous volumes of food with high precision. However, this centralization creates a "brittle" system. A failure at a single major hub can ripple through the entire network, leading to widespread shortages and massive localized loss. Furthermore, centralized systems often require long transport distances, which increases the time-to-market and the risk of degradation during transit.

Decentralized architectures, characterized by smaller, distributed nodes located closer to the point of production, offer a more robust alternative. By reducing the distance between the farm and the first point of cooling or processing, decentralized systems can capture the biological value of the product more effectively. In the event of a systemic shock, a decentralized network is less likely to collapse entirely, as the failure of one node does not necessarily compromise the others. However, decentralization often comes with higher per-unit costs and greater difficulty in maintaining standardized quality control. The engineering challenge of the twenty-first century is to design "hybrid" systems that leverage the strengths of both models—using centralized hubs for long-term storage of staples while fostering a mesh-like network of regional facilities for perishables.

This structural debate also has profound implications for regional food sovereignty. Decentralized systems empower local communities by providing them with the infrastructure to manage their own food supplies. This is particularly important in regions prone to geopolitical instability or extreme climate events, where the ability to store and process food locally can be a matter of survival. Policy interventions should therefore aim to balance the drive for industrial efficiency with the need for community-level resilience. This might involve subsidies for small-scale modular infrastructure and the development of regional "food hubs" that aggregate the produce of multiple smallholders, providing them with the collective scale needed to access high-value markets.

7. Sustainable Packaging and the Circular Economy

Packaging is a dual-edged sword in the post-harvest system. On one hand, it is essential for protecting food from physical damage, moisture loss, and contamination. On the other hand, the proliferation of single-use plastics in food packaging has created an environmental crisis of its own. Advances in post-harvest technology are increasingly focused on the development of "active" and "intelligent" packaging that is also biodegradable or recyclable. Active packaging goes beyond a simple barrier; it incorporates scavengers that remove ethylene or oxygen from the package environment, or antimicrobial agents that inhibit the growth of spoilage organisms.

Intelligent packaging uses chemical or electronic indicators to provide information about the history and condition of the product. Time-temperature indicators (TTIs) can change color if a product has been exposed to unsafe temperatures, providing a simple yet effective way to ensure food safety and reduce unnecessary disposal based on conservative date labels. The transition toward a circular economy requires that these packaging materials be integrated into a closed-loop system. This involves the use of bio-based polymers derived from agricultural waste—effectively using the "loss" from one part of the system to protect the "yield" of another. The engineering of these materials must ensure that they provide the necessary protective properties while still being able to break down in industrial or home composting environments.

The deployment of sustainable packaging also requires significant changes in waste management infrastructure. Bio-based plastics often require specific conditions for degradation that are not present in traditional landfills. A truly sustainable post-harvest system must therefore align packaging technology with the available recycling and composting facilities. This is a classic example of a "locked-in" system, where the dominance of petroleum-based plastics is reinforced by existing collection and processing networks. Overcoming this lock-in requires a combination of extended producer responsibility (EPR) policies, which hold companies accountable for the entire lifecycle of their packaging, and public investment in the "missing" infrastructure for organic and bio-plastic waste.

8. Infrastructure Robustness in the Face of Climate Change

Climate change is not a future threat to the post-harvest system; it is a present reality that is already increasing the rates of food loss. Rising temperatures accelerate the physiological decay of produce and create more favorable conditions for pests and pathogens. Extreme weather events, such as floods and hurricanes, can destroy storage facilities and sever transport links, leading to catastrophic losses in a matter of hours. The engineering of post-harvest infrastructure must therefore transition from "designing for average conditions" to "designing for extremes." This involves increasing the physical robustness of storage structures and the redundancy of logistical networks.

Climate-proofing the post-harvest chain requires a rethink of structural design. Storage facilities must be able to withstand higher wind loads and be elevated above potential flood zones. The use of natural refrigerants with low global warming potential is also essential to ensure that the infrastructure itself does not contribute to the climate feedback loop. Furthermore, the "biological robustness" of the system can be enhanced through the breeding and cultivation of crop varieties that are naturally more resistant to post-harvest stressors. This interdisciplinary approach—linking genetics with engineering—is necessary to create a food system that is truly resilient.

Adaptation also involves the use of "anticipatory governance" to manage the risks associated with a changing climate. Governments must develop comprehensive risk assessments for their national food infrastructures and identify the most vulnerable points. This might lead to the strategic relocation of key logistical hubs or the development of "emergency cold chain" capabilities that can be deployed during disasters. The goal of robustness is not to create a system that never fails, but to create one that fails gracefully and can be rapidly restored. In the context of global food security, the robustness of the post-harvest chain is a critical buffer that protects human populations from the increasing volatility of the primary production system.

9. Fairness, Equity, and the Democratization of Technology

The benefits of advanced post-harvest technology are currently distributed in a highly unequal manner. Smallholder farmers, who produce a significant portion of the world's food, often lack the capital and infrastructure to adopt even basic preservation techniques. This "technology gap" traps them in a cycle of poverty and loss, as they are forced to sell their produce immediately after harvest when prices are lowest. Democratizing post-harvest technology is therefore a moral imperative and a functional requirement for global food security. This requires a shift from "top-down" technology transfer to "bottom-up" co-innovation.

Democratization involves the design of technologies that are appropriate for the local context. A high-tech, automated warehouse that requires a stable 24-hour power grid is of little use to a rural community in a developing nation. Instead, the focus should be on "frugal innovation"—solutions that are low-cost, easy to maintain, and integrated with local knowledge. Evaporative cooling chambers, for example, use the natural process of evaporation to lower temperatures and can be built by local artisans using readily available materials. When these traditional methods are augmented with modern data-driven management, they can provide a powerful and sustainable way to reduce loss.

Furthermore, the "social architecture" of the supply chain must be redesigned to ensure that value is distributed fairly. This includes the support of farmer cooperatives and the development of transparent pricing mechanisms that reward farmers for the quality and longevity of their produce. If a farmer invests in better harvesting or storage techniques, they should receive a premium that reflects the reduced loss and increased shelf life of their products. Without these economic incentives, even the most advanced technology will remain unused. Fairness and equity are not just social goals; they are the feedback mechanisms that ensure the long-term viability and adoption of sustainable practices.

10. Policy Frameworks and Global Governance

The modernization of post-harvest systems cannot be left to the market alone. The systemic nature of food loss requires coordinated policy interventions at the local, national, and international levels. Currently, global agricultural policy is heavily skewed toward production subsidies, with relatively little funding directed toward the post-harvest sector. A rebalancing of these priorities is essential. This involves the creation of "loss reduction targets" in national agricultural plans and the integration of post-harvest management into international climate and development goals.

Policy must also address the "regulatory fragmentation" that hinders the deployment of new technologies. Different standards for food safety, packaging, and data sharing across different jurisdictions create significant barriers for international trade and logistical efficiency. Harmonizing these standards would allow for more seamless movement of food and the wider adoption of innovative solutions like intelligent packaging. Furthermore, governments should use public procurement as a lever to drive change. By requiring that food purchased for schools, hospitals, and the military be managed through "low-loss" supply chains, the public sector can create a guaranteed market for sustainable technologies and practices.

International cooperation is particularly important for managing global food crises. The development of an "international food loss database" could provide real-time information on the status of global stocks and the efficiency of different logistical corridors. This would allow for more informed humanitarian responses and help to stabilize global prices. The governance of post-harvest technology must also address the "digital sovereignty" of nations. As the food system becomes increasingly data-driven, it is essential that all countries have the capacity to manage their own data and are not dependent on a few multinational tech firms. This involves investing in local digital infrastructure and training a new generation of interdisciplinary "food systems engineers" who can bridge the gap between technology and society.

11. Forward-Looking Perspectives: Regenerative and Generative Systems

As we look toward the future, the goal of post-harvest management should move beyond "loss reduction" toward the creation of "generative systems." A generative food system is one that actively improves the environment and social health through its operation. This might involve the use of "mobile processing units" that travel from farm to farm, converting potential waste into shelf-stable, high-value products on-site. It could also involve the integration of urban vertical farming with hyper-local distribution networks, virtually eliminating the need for long-distance transport and complex cold chains for certain types of produce.

The concept of "molecular preservation" is another exciting frontier. Scientists are exploring ways to use edible coatings made from silk or other natural proteins that can dramatically slow down the respiration and moisture loss of fruits and vegetables without the need for plastic packaging or continuous refrigeration. If these coatings can be applied at the farm level using simple, low-cost methods, they could transform the economics of the entire supply chain. From a systems perspective, this represents a "dematerialization" of the infrastructure—replacing heavy, energy-intensive hardware with smart, biological software.

Ultimately, the future of post-harvest technology lies in its ability to adapt to a world that is increasingly volatile and resource-constrained. The rigid, linear supply chains of the past must give way to flexible, circular, and intelligent networks. This requires a fundamental shift in how we value food. If we treat food as a precious biological resource rather than a cheap commodity, the "cost" of investing in advanced preservation technology becomes much easier to justify. The transition to a zero-loss food system is a massive undertaking, but it is one of the most effective ways to ensure that the planet can continue to feed its growing population while staying within its ecological limits.

12. Conclusion

The advances in post-harvest technology discussed in this paper offer a powerful set of tools for addressing one of the most persistent failures of the global agricultural system. However, the successful deployment of these technologies requires more than just engineering excellence; it requires a systemic vision that integrates biological requirements, infrastructural robustness, and social fairness. The transition from a "produce-and-forget" model to a "preserve-and-protect" model is essential for achieving global food security. This transition is not without its trade-offs, particularly regarding the centralization of power and the environmental footprint of new technologies.

By prioritizing decentralized resilience, democratizing access to data and infrastructure, and aligning economic incentives with sustainability, we can create a post-harvest system that is truly fit for the twenty-first century. The integration of IoT, AI, and sustainable packaging into a cohesive socio-technical framework represents a paradigm shift in how we manage the global flow of calories and nutrients. As we continue to refine these technologies, we must remain vigilant about their broader social and ecological impacts, ensuring that the drive for efficiency never comes at the expense of equity or the health of the planet. The goal is a generative food system where loss is not an inevitability, but a design flaw that we have finally learned to overcome.

References

1. Aday, M. S., & Caner, C. (2014). The shelf life extension of fresh strawberries using an active packaging system. Packaging Technology and Science, 27(3), 197-212.

2. Affognon, H., et al. (2015). Economic analysis of post-harvest loss reduction interventions in the grain supply chain in sub-Saharan Africa. Food Policy, 53, 22-35.

3. Béné, C., et al. (2019). Resilience in the context of food systems: Rethinking the concept of resilience in the face of environmental and social change. World Development, 119, 1-14.

4. Bourne, M. C. (2002). Postharvest Food Losses of Fruits and Vegetables in Developing Countries. Academic Press.

5. Chen, X., & Zhu, Q. (2022). Artificial intelligence in agricultural supply chain management: A systematic literature review. Journal of Cleaner Production, 345, 131-152.

6. Dauvergne, P. (2020). AI in the Wild: Sustainability in the Age of Artificial Intelligence. MIT Press.

7. Foley, J. A., et al. (2011). Solutions for a cultivated planet. Nature, 478(7369), 337-342.

8. Garnett, T. (2011). Where are the best opportunities for reducing greenhouse gas emissions in the food system? Food Policy, 36, S23-S32.

9. Godfray, H. C. J., et al. (2010). Food security: The challenge of feeding 9 billion people. Science, 327(5967), 812-818.

10. Gustavsson, J., Cederberg, C., & Sonesson, U. (2011). Global food losses and food waste: Extent, causes and prevention. FAO.

11. Hajshirmohammadi, A. (2022). Sustainability and Circularity in Food Supply Chains. Springer Nature.

12. Hodges, R. J., Buzby, J. C., & Bennett, B. (2011). Postharvest losses and waste in developed and less developed countries: Opportunities to improve resource use. The Journal of Agricultural Science, 149(S1), 37-45.

13. Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. International Journal of Production Research, 58(10), 2904-2915.

14. Kader, A. A. (2005). Increasing food availability by reducing postharvest losses of fresh

produce. Acta Horticulturae, 682, 2169-2176.

15. Kasso, M., & Bekele, A. (2018). Post-harvest loss and quality deterioration of horticultural crops in Ethiopia: A review. Journal of Plant Science and Agriculture Research, 2(2), 1-10.

16. Kitinoja, L., et al. (2011). Postharvest technology for developing countries: Challenges and opportunities in research, outreach and advocacy. Journal of the Science of Food and Agriculture, 91(4), 597-603.

17. Kumar, A., & Kalita, P. K. (2017). Reducing postharvest losses during storage of grain crops to strengthen food security in developing countries. Foods, 6(1), 8.

18. Lang, T., & Barling, D. (2012). Food security and food sustainability: Reformulating the debate. The Geographical Journal, 178(4), 313-326.

19. Lee, H. L. (2004). The triple-A supply chain. Harvard Business Review, 82(10), 102-113.

20. Murdock, L. L., & Baoua, I. B. (2014). On solar drying of cowpea seeds. Journal of Stored Products Research, 58, 20-25.

21. Parfitt, J., Barthel, M., & Macnaughton, S. (2010). Food waste within food supply chains: Quantification and potential for change to 2050. Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1554), 3065-3081.

22. Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987-992.

23. Rao, P. S., et al. (2014). High pressure processing of foods: An overview. Trends in Food Science & Technology, 38(1), 4-22.

24. Sarkis, J. (2021). Supply chain sustainability: Learning from the COVID-19 pandemic. International Journal of Operations & Production Management, 41(1), 63-73.

25. Springmann, M., et al. (2018). Options for keeping the food system within environmental limits. Nature, 562(7728), 519-525.

26. Stathers, T., et al. (2013). Postharvest agriculture in Sub-Saharan Africa: Pitfalls and priorities for food security. Food Chain, 3(1-2), 10-31.

27. Tefera, T. (2012). Post-harvest losses in African maize in the face of feeding a growing population. Food Security, 4(2), 267-277.

28. Tseng, M. L., et al. (2019). Sustainable food supply chain management: A holistic review.

Resources, Conservation and Recycling, 146, 11-21.

29. United Nations. (2022). The State of Food Security and Nutrition in the World. FAO/IFAD/UNICEF/WFP/WHO.

30. Vermeulen, S. J., Campbell, B. M., & Ingram, J. S. (2012). Climate change and food systems. Annual Review of Environment and Resources, 37, 195-222.

31. Yahia, E. M. (2019). Postharvest Technology of Perishable Horticultural Commodities. Woodhead Publishing.

32. Zhu, Q., & Sarkis, J. (2004). Relationships between operational practices and performance among early adopters of green supply chain management practices in Chinese manufacturing enterprises. Journal of Operations Management, 22(3), 265-289.