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Post-Harvest Intelligence for Reducing Food Loss in Decentralized Markets

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Abstract

Post-harvest food loss remains a persistent constraint on food availability, farmer income, market efficiency, and resource sustainability, particularly in decentralized food systems characterized by small farms, fragmented trading networks, informal wholesale markets, limited cooling infrastructure, variable transportation conditions, and incomplete information about product quality and demand. Conventional post-harvest management frequently responds to visible deterioration only after substantial quality loss has already occurred. Post-harvest intelligence offers a different approach by combining measurement, sensing, shelf-life estimation, market information, storage conditions, logistics data, and decision support to identify deterioration risks before products become unsalable. This conceptual review examines how post-harvest intelligence can reduce food loss in decentralized markets through affordable and context-appropriate digital and physical infrastructure. Current FAO information indicates that approximately 13.2% of food is lost globally after harvest and before retail, demonstrating that substantial food-system value is lost before products reach consumers. The paper synthesizes recent evidence concerning Internet of Things sensors, artificial intelligence, digital twins, smart cold chains, solar-powered decentralized cooling, quality monitoring, grain-storage technologies, market information, and smallholder adoption. Particular attention is given to the distinction between collecting data and creating actionable intelligence.

A temperature sensor has limited value unless its measurements influence storage, routing, pricing, or selling decisions. Similarly, artificial intelligence becomes useful only when predictions can be converted into practical action within the limited time and financial resources available to decentralized market actors. A 2025 digital twin study demonstrated simulated food-loss reductions of 8.6% for strawberries, 12.1% for lychees, 13.6% for oranges, and 15.5% for apples through improved temperature and remaining-shelf-life intelligence. Evidence from 1,001 smallholder vegetable farmers in Ghana further shows the importance of access and usability: farmers reported average post-harvest losses of 25%, while 79% expressed willingness to adopt solar-powered cold storage, despite limited access to post-harvest training and extension services. The study concludes that effective post-harvest intelligence should be decentralized, affordable, interoperable, commodity-sensitive, and directly connected with decisions concerning harvest timing, cooling, storage, sorting, transport, market selection, and product prioritization. Technology should therefore function as a decision-support layer within local food markets rather than as an isolated digital intervention.

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1. Introduction

Food production does not create nutritional or economic value merely because a crop has been successfully harvested. Agricultural products must remain sufficiently safe, nutritious, physically intact, and commercially acceptable while they move from farms through handling, aggregation, transportation, storage, wholesale markets, processing, and retail. Failure at any of these stages can transform productive agricultural output into physical loss, quality deterioration, price discount, or complete rejection.

The scale of this challenge remains substantial. FAO currently reports that approximately 13.2% of food is lost globally after harvest and before the retail stage, while additional food is wasted later at retail, food-service, and household levels. Food loss and waste also contribute significantly to greenhouse-gas emissions and reduce the efficiency with which land, water, energy, fertilizer, labor, and capital are used throughout food systems. Reducing post-harvest loss consequently creates value without requiring an equivalent increase in cultivated land or agricultural production.

challenge is particularly complex in decentralized markets. In such systems, production is distributed across many small or medium farms and food moves through multiple local collectors, transporters, street vendors, wholesalers, cooperatives, informal markets, and small retailers. Infrastructure and management practices may vary sharply even within the same geographic region. One farmer may have access to a packhouse, another may sell directly after harvest, while a third may transport produce for several hours without cooling. Product condition therefore depends on a chain of numerous small decisions rather than one centrally controlled logistics system.

Decentralization itself should not be considered a weakness. Local and regional markets provide important economic and food-access functions and can connect producers with consumers without requiring highly centralized distribution. Their difficulty lies in coordinating highly perishable products when information concerning temperature, remaining shelf life, market demand, product location, handling history, and available storage capacity is incomplete.

Fresh produce illustrates this problem clearly. Fruits and vegetables remain biologically active after harvest. Respiration, transpiration, enzymatic changes, microbial activity, mechanical injury, temperature, relative humidity, and atmospheric conditions interact continuously to influence marketable life. A tomato that looks acceptable during loading may deteriorate rapidly after several hours of heat exposure. Another batch harvested on the same day may retain substantially greater shelf life because it was shaded, cooled, or handled differently.

Traditional post-harvest management often relies on generalized assumptions such as selling the oldest stock first or transporting all produce to the usual market. These rules remain useful but do not always correspond with biological reality. The oldest harvested batch may not necessarily be the batch with the shortest remaining shelf life. A newer batch exposed to excessive temperature may require more urgent sale. This distinction creates the basis for post-harvest intelligence.

Post-harvest intelligence can be defined as the systematic conversion of product, environmental, logistical, and market data into timely decisions that protect food quantity, quality, and economic value after harvest. Its purpose is not simply digital monitoring. The objective is to determine which product is deteriorating, where deterioration risk is highest, which intervention is economically justified, and which market or processing route can recover the greatest remaining value.

This perspective integrates technologies that have often been studied separately. Sensors provide temperature, humidity, gas, moisture, or location information. Artificial intelligence can interpret complex quality patterns. Shelf-life models estimate remaining marketable life. Digital twins represent changing product conditions through virtual models. Cold storage slows deterioration. Mobile platforms communicate decisions. Market information can help determine whether products should be stored, sold immediately, redirected, processed, or discounted.

Recent research increasingly supports this integrated direction. Zou and colleagues combined digital-twin and artificial-intelligence techniques to predict in-box temperature and remaining shelf life in fruit supply chains. Their framework achieved temperature prediction errors below ±0.3°C under the reported experimental conditions and shelf-life estimation errors under ±1.2 days for highly perishable products such as strawberries and lychees. Their simulations indicated meaningful reductions in food loss across multiple fruits when quality-aware management was compared with simpler ambient-temperature approaches.

Sensor-driven cold-chain research similarly demonstrates a shift from monitoring temperature as a compliance variable toward using sensor information to estimate product quality. Elashmawy and colleagues developed the concept of a digital cold chain in which sensor measurements and artificial intelligence support product-quality assessment rather than merely recording whether a temperature threshold was crossed. This transition is important because food deterioration is cumulative. A single temperature limit may not adequately describe the consequences of repeated short exposures or different product sensitivities.

However, advanced post-harvest intelligence developed for large export chains cannot simply be transferred unchanged into decentralized markets. A small vegetable farmer, informal wholesaler, or street-market trader cannot necessarily install dozens of high-cost sensors, maintain cloud subscriptions, or employ specialized data analysts. Intelligence must therefore be proportional to the value of the commodity and the capacity of the user.

This paper develops a decentralized interpretation of post-harvest intelligence. It argues that the most useful system is not necessarily the one collecting the greatest amount of data but the one producing the highest-value decisions with the minimum technically sufficient information.

2. Evidence Base, Research Gap and Objectives

Recent post-harvest research shows that losses emerge through interactions among biological deterioration, storage conditions, physical handling, transportation, market access, and managerial capability. Belemu and Oluwatayo investigated post-harvest losses among a random sample of 224 smallholder fruit farmers in South Africa's Vhembe District. More than half of respondents reported experiencing post-harvest losses, with inadequate storage, mechanical damage during transportation, excessive transpiration, improper handling, and biodeterioration identified among the major causes.

Only 34.82% of the farmers reported using practices or technologies intended to minimize post-harvest loss.

The findings are significant because they demonstrate that food loss cannot be explained solely by the absence of refrigeration. Storage, transportation, product physiology, handling skills, and access to information are interconnected. Improving one element while ignoring the others can produce only partial results.

Grain systems have different biological characteristics but similarly demonstrate the importance of post-harvest management. Nath, Chen, O'Sullivan, and Zare reviewed technologies for reducing grain post-harvest losses and emphasized appropriate harvesting, drying, moisture control, storage, pest management, handling, and monitoring as critical components of loss prevention. Grain intelligence therefore differs from fresh-produce intelligence. Temperature and remaining shelf life may dominate decisions for highly perishable produce, whereas grain systems require particular attention to moisture migration, insects, fungi, mycotoxin risk, storage integrity, and safe drying.

Recent fruit and vegetable research has expanded the range of preservation options beyond conventional refrigeration alone. Rizzo's 2025 review examined sustainable post-harvest innovations intended to extend fruit and vegetable shelf life and minimize loss through improved preservation, packaging, storage, and quality-management strategies. These technologies reinforce the principle that intelligence should determine which physical intervention is justified rather than being treated as a replacement for preservation technologies.

Artificial intelligence adds another analytical layer. Machine-learning methods can identify visual defects, estimate maturity, classify quality, and predict deterioration using imaging, spectral, environmental, or sensor data. A recent review of AI in fruit-quality monitoring describes increasing use of imaging, spectroscopy, electronic sensing, and multimodal information for ripeness and damage detection, while also noting persistent challenges involving sensor cost, standardization, and robustness under real operating conditions.

IoT systems create the connectivity required to move this information between products, storage spaces, vehicles, and decision-makers. Zhang and colleagues reviewed IoT applications across fresh-fruit supply chains and highlighted their role in monitoring environmental conditions, supporting product authentication, predicting shelf life, and improving supply-chain decisions. Yet continuous connectivity cannot be assumed in every decentralized market. Systems may need to store measurements locally and synchronize periodically where mobile data or electricity is unreliable.

Cold-chain intelligence is becoming increasingly sophisticated. Han and colleagues' recent review of smart cold-chain logistics identifies sensing, monitoring, information integration, and predictive decision support as central directions for fresh agricultural products. These advances provide useful technological principles, but decentralized-market implementation raises different questions of affordability, shared infrastructure, service models, local repair capacity, and user training.

The importance of these adoption conditions is demonstrated by Kansanga and colleagues. Their 2025 study surveyed 1,001 smallholder vegetable farmers in Ghana concerning willingness to adopt solar-powered cold storage. Seventy-nine percent expressed willingness to adopt the technology. Farmers reported average post-harvest loss of 25%, yet only 26% had received post-harvest loss training and only 20% had ready access to extension services. The study further showed that economic capacity, profitability, training, access to agricultural information, perceptions of food loss, and farm context affected willingness to adopt.

These findings reveal the principal research gap addressed by the present paper. Considerable research exists on individual technologies such as cooling, sensors, artificial intelligence, digital twins, storage, packaging, and market information. Less attention has been given to how these components should be assembled into a minimum viable intelligence architecture appropriate for decentralized agricultural markets.

A second gap concerns decision relevance. Many technologies measure conditions without clearly explaining which operational decision should follow. Temperature monitoring has little value if produce continues to remain in the same deteriorating environment because there is no alternative storage or transport option. Market-price information has limited value if the product will spoil before it reaches the more profitable market. Post-harvest intelligence therefore requires simultaneous consideration of biological time and economic opportunity.

A third gap concerns product differentiation. Conventional inventory management commonly prioritizes products according to arrival sequence. Perishable food may require a different logic based on remaining shelf life. Products approaching deterioration should sometimes move first even when they entered storage later.

The objective of the present research is consequently to develop an integrated conceptual framework for post-harvest intelligence in decentralized markets. The study examines how product sensing, shelf-life prediction, decentralized cooling, market information, handling decisions, and logistics can be combined to reduce avoidable food loss. It additionally evaluates the socioeconomic requirements for adoption and identifies boundaries beyond which sophisticated technologies may provide insufficient economic return.

Table 1: Selected Evidence Informing the Post-Harvest Intelligence Framework

Study	Context	Key Evidence	Relevance to Decentralized Markets
Nath et al., 2020	Grain post-harvest systems	Storage, drying, moisture, pests, and monitoring strongly influence grain loss	Demonstrates commodity-specific intelligence needs
Kansanga et al., 2020	1,001 vegetable farmers in Ghana	25% average reported post-harvest loss; 79% willing to adopt solar cooling	Shows both strong need and adoption potential
Belemu and Oluwatayo, 2021	224 smallholder fruit farmers, South Africa	Storage, transport damage, transpiration, handling, and biodeterioration were major loss causes	Demonstrates multidimensional origins of food loss
Elashmawy et	Digital cold chain	Sensor data combined with AI for	Moves monitoring from

Study	Context	Key Evidence	Relevance to Decentralized Markets
al., 2021		product-quality assessment	condition recording to quality intelligence
Zou et al., 2019	Fruit cold supply chain	Digital twin and AI predicted temperature and remaining shelf life	Demonstrates quality-aware decision potential
Rizzo, 2019	Fruits and vegetables	Sustainable preservation technologies can extend marketable life	Connects intelligence with physical preservation options
Han et al., 2020/2021	Fresh agricultural cold chains	Smart sensing, logistics, and predictive technologies are becoming integrated	Supports system-level post-harvest intelligence

Source: Author synthesis from the cited literature. No new empirical observations are claimed in this table.

3. Methodology and Proposed Post-Harvest Intelligence Framework

The present study employs a structured conceptual review rather than a completed field experiment or formal meta-analysis. Recent peer-reviewed and institutional evidence was examined with emphasis on food-loss measurement, post-harvest handling, smart cold chains, sensors, artificial intelligence, digital twins, decentralized cooling, storage technologies, smallholder adoption, and local market conditions. Evidence published primarily from 2024 to August 2026 was prioritized while earlier foundational work was retained where necessary.

The framework begins with loss measurement. A decentralized market cannot intelligently reduce food loss unless it knows where and why loss is occurring. FAO's food-loss platform emphasizes the importance of measurement because reliable information makes it possible to identify loss hotspots and support informed interventions from farm to market. Recording should therefore distinguish complete physical loss from quality discount, trimming, rejection, spoilage, pest damage, transport damage, and deterioration occurring during storage.

The second layer is product identity. Intelligence cannot operate on an undefined mass of food. Produce needs at least a batch-level identity linked to crop type, approximate harvest time, quantity, source, and relevant quality characteristics. Individual-unit traceability is unnecessary for most low-value decentralized produce; batch-level identification can provide sufficient decision value at substantially lower cost.

The third layer concerns environmental condition. Temperature and humidity are particularly important for perishables, while grain systems additionally require moisture-content information. Sensors do not need to be installed on every crate. Strategically located devices can provide useful information when the physical environment is sufficiently homogeneous. Zou and colleagues demonstrated that digital-twin modeling can partly extend sparse sensor information across hierarchical packaging units, although prediction errors increase as representation moves from smaller to larger units.

The fourth layer is quality-state estimation. Environmental measurements should be converted into an estimate of what they mean for the food. Two lots exposed to the same air temperature may respond differently because of crop variety, maturity, initial temperature, packaging, airflow, mechanical injury, and physiological condition. Intelligence therefore requires commodity-specific interpretation.
Remaining shelf life represents one of the most valuable forms of post-harvest intelligence. Instead of asking only when a product was harvested, market actors can ask how much marketable life remains under current conditions. This changes inventory management from first-in-first-out toward first-expire-first-out where appropriate.

The fifth layer consists of market intelligence. Biological preservation has economic value only when a viable market exists. Farmers and traders need information about demand, prices, congestion, transportation time, buyer requirements, processing options, and potential secondary markets. A product with one day of remaining shelf life should not be routed toward a distant market merely because the nominal selling price there is higher.

The decision objective should therefore consider expected recoverable value. A simple conceptual relationship can be written as:

Expected Recoverable Value = Expected Selling Price × Probability of Marketable Arrival − Handling − Storage − Transport − Transaction Costs

The probability of marketable arrival depends on current product condition, remaining shelf life, transport duration, expected temperature exposure, packaging, and handling risk. Post-harvest intelligence improves this probability estimate rather than assuming that all products arriving at a market will retain equivalent quality.

The sixth layer is intervention selection. Intelligence must lead to an operational response. Possible responses include immediate sale, shading, evaporative cooling, refrigerated storage, solar-powered cooling, regrading, repackaging, rerouting, accelerated transport, processing, controlled ripening, discounted sale, donation, or conversion into another safe marketable product.

Cooling deserves particular attention because temperature is one of the strongest determinants of deterioration rate in many fresh products. However, centralized refrigeration infrastructure is frequently inaccessible in dispersed rural areas. Decentralized solar-powered cold storage offers an alternative where conventional electricity is unreliable. Research on decentralized solar cooling emphasizes its potential for fresh fruit and vegetable systems in infrastructure-constrained settings.

Shared infrastructure can substantially improve economic feasibility. Instead of requiring each farmer to purchase an individual refrigeration unit, cooperatives, producer organizations, wholesalers, municipalities, or private service providers can offer cooling capacity through fee-for-service models. Kansanga and colleagues discuss the relevance of recurring service fees and the importance of farmer profitability in determining whether shared cooling technologies remain financially usable after adoption.

Post-harvest intelligence should consequently include storage-capacity information. A mobile system could show available cooling space at nearby facilities alongside price, distance, and expected travel time. This turns cold storage from a passive building into part of an information network.

The seventh layer is decision communication. A technically accurate model that presents complex probabilities or raw sensor data may be ineffective for users who need immediate operational guidance. Farmer-facing or trader-facing systems should communicate decisions in direct terms, such as "sell today," "cool within two hours," "priority batch," "safe to hold until tomorrow," or "route to processing."

This does not require hiding uncertainty. Recommendations should indicate when confidence is low or when physical inspection is required. Human judgment remains essential where disease, bruising, contamination, or unusual product conditions cannot be reliably identified through the available sensors. For future empirical validation, the framework could be evaluated through a five-item stakeholder questionnaire. These questions are proposed only and were not administered in the present review.

Table 2: Proposed Five-Item Questionnaire for Future Field Validation

No.	Proposed Question
1	At which stage do you currently experience the greatest post-harvest food loss: handling, storage, transport, or market sale?
2	Which information would most improve your daily post-harvest decisions: product quality, remaining shelf life, storage availability, market price, or transport time?
3	How often are you forced to sell perishable produce quickly because suitable storage is unavailable?
4	Would you use a low-cost digital service that identified which batches should be sold, stored, or transported first?
5	What maximum service cost would remain affordable if post-harvest intelligence measurably reduced your product losses?

Note: The questionnaire is proposed for future empirical research and has not been administered.

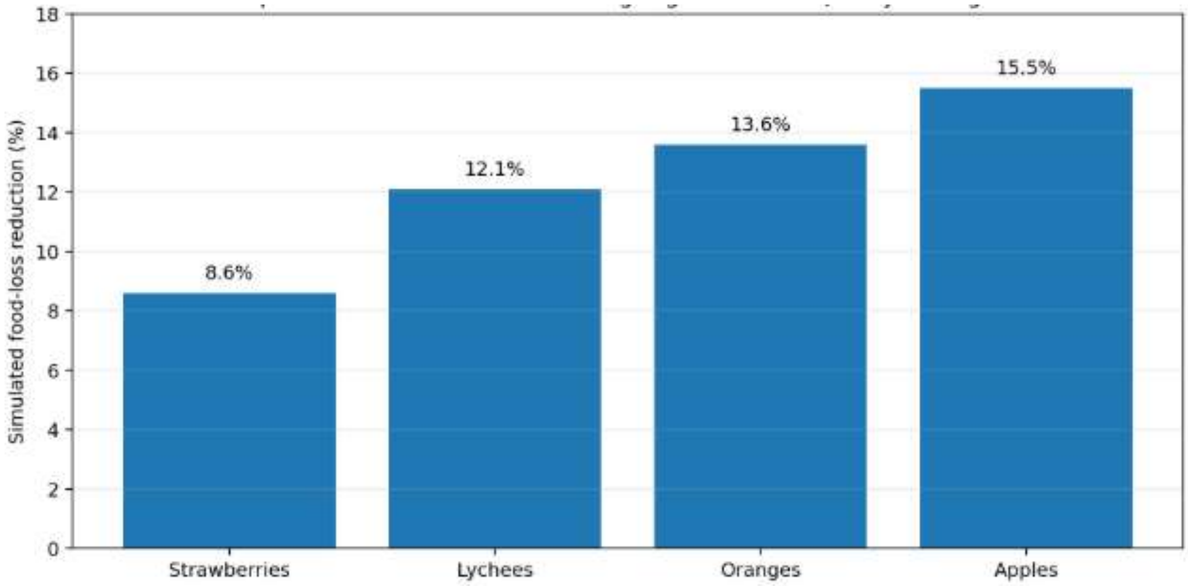
4. Results and Discussion

The synthesis indicates that post-harvest intelligence can reduce loss through four principal mechanisms: earlier detection, better prioritization, improved intervention timing, and more informed market allocation. Its strongest value emerges when decisions are made before visible deterioration becomes severe.

The first major result concerns remaining-shelf-life intelligence. Conventional cold-chain monitoring frequently treats temperature as the final variable of interest. Quality-aware systems instead treat temperature as an input into biological deterioration. Zou and colleagues' digital-twin framework used experimentally verified temperature information together with an LSTM forecasting approach and a kinetic shelf-life model. Their system achieved a reported temperature prediction error below ±0.3°C and estimated remaining shelf life with an error below ±1.2 days for highly perishable fruits under the studied conditions.

The food-loss implications were significant in simulation. The integrated digital twin–AI approach reduced modeled losses by different amounts depending on the fruit commodity, demonstrating that the value of post-harvest intelligence is product-specific rather than uniform.

Graph 1: Food-Loss Reduction Using Digital Twin–AI Quality Intelligence



Source: Author-prepared graph based on Zou et al. (2025). Values represent simulated food-loss reductions reported for the digital twin–AI system and should not be interpreted as universal field-market loss reductions.

The graph shows an 8.6% simulated reduction for strawberries, 12.1% for lychees, 13.6% for oranges, and 15.5% for apples. These differences are important because they demonstrate that one predictive model or intervention cannot automatically be assumed to generate the same outcome for every food. Commodity physiology, initial quality, supply-chain duration, and deterioration kinetics affect achievable results.

The second major result is that intelligence must be connected with physical capacity. A model may correctly predict that a batch requires immediate cooling, but loss will continue if no cooling facility exists. This is particularly relevant in smallholder systems. Kansanga and colleagues found that surveyed Ghanaian vegetable farmers reported average losses of 25% of harvest and traveled an average of 21 km to the nearest market. Seventy-nine percent were willing to adopt solar-powered cold storage, yet only 26% had received post-harvest management training and 20% had ready access to extension services.

These results illustrate a central principle: post-harvest intelligence is both informational and infrastructural. Digital systems identify what should happen, while storage, transport, packaging, labor, finance, and markets determine whether that recommendation can actually be implemented.

The third result is that decentralized cooling can provide strategic value beyond simple preservation. Cooling extends decision time. A farmer without storage may be forced to accept the first available buyer because biological deterioration reduces bargaining power with every passing hour. Cooling creates temporal flexibility, allowing the product to wait for aggregation, scheduled transport, or a more suitable market.

This economic function helps explain high stated willingness to adopt solar cooling among farmers experiencing substantial losses. Yet adoption cannot be assumed from willingness alone. The Ghana study found that profitability, wealth, training, access to information, technology experience, perceptions of food loss, crop type, and farm characteristics influenced adoption. Technology programs should therefore avoid assuming that equipment distribution automatically generates sustained use.

The fourth result concerns market routing. Decentralized markets frequently experience temporary gluts in which many farmers harvest the same crop simultaneously. Prices fall while unsold produce deteriorates. A post-harvest intelligence platform can combine supply information with remaining shelf life to recommend alternative nearby markets, processors, institutions, restaurants, food-service buyers, or storage facilities.

This requires careful interpretation of price signals. A higher price in another market does not necessarily create a better outcome if additional transport duration increases spoilage risk. The decision should therefore optimize recoverable value rather than headline price.

The fifth result is that product prioritization should become quality-aware. First-in-first-out inventory systems are easy to operate, but biological age and chronological age are not always identical. A lot that experienced two hours of excessive heat may possess less remaining shelf life than an earlier lot maintained under appropriate conditions.

First-expire-first-out systems use predicted deterioration rather than arrival time alone. Digital cold-chain research increasingly supports this quality-driven approach by linking sensor histories with expected product condition.

The sixth result concerns the role of artificial intelligence. AI should not be treated as an independent solution. Its value lies in detecting patterns that would otherwise be difficult to interpret quickly. Imaging systems can support grading, spectral techniques can reveal properties that are not visible externally, and predictive models can estimate quality changes under variable conditions. Recent research nevertheless continues to identify cost, model transferability, field robustness, and standardization as barriers to broad deployment.

For decentralized markets, this suggests that edge intelligence may often be more useful than computationally intensive centralized systems. A low-cost mobile device capable of classifying visible defects or estimating ripeness can provide immediate value even without continuous internet access. Complex models should be reserved for applications where the additional accuracy justifies additional cost.

The seventh result is that intelligence requirements differ between perishables and durable commodities. Grain post-harvest management requires monitoring of moisture, pests, temperature, fungal conditions, drying, and storage integrity. Nath and colleagues emphasize that improved technologies across harvesting, drying, storage, handling, monitoring, and pest management can substantially strengthen grain-loss prevention.

This difference prevents a universal post-harvest intelligence platform from relying on one fixed set of indicators. Commodity profiles should determine which variables are measured. A tomato and a stored bag of maize have fundamentally different deterioration risks.

The eighth result is that simple handling intelligence can be as valuable as advanced AI. Belemu and Oluwatayo found that smallholder fruit farmers identified poor storage, transportation damage, transpiration, improper handling, and biodeterioration as important sources of loss. More than half of respondents experienced post-harvest loss, while only about one-third used practices or technologies intended to minimize it.

A post-harvest intelligence system should therefore not assume that every recommendation must be technological. An alert that recommends shade, removal of damaged fruits, improved crate stacking, faster unloading, or separation of diseased produce may prevent more loss than an expensive algorithm.
The ninth result concerns data reliability. Sensors themselves can fail, drift, lose connectivity, or be placed in unrepresentative locations. Digital intelligence should therefore incorporate data-quality checks. Sudden impossible temperature changes, missing readings, or values inconsistent with neighboring sensors should trigger inspection rather than automatic action.

Human observation remains an important validation layer. A trader who observes unexpected bruising or fermentation should be able to override a model that indicates adequate shelf life. Intelligence should strengthen rather than suppress informed human judgment.

The tenth result is that food-loss reduction should distinguish between physical preservation and value preservation. Produce may remain edible but lose market grade because of appearance, softness, size, or minor damage. Intelligence can support alternative allocation before complete loss occurs.

5. Practical Implications and Future Direction

Implementation should begin with loss mapping rather than equipment procurement. Market authorities, cooperatives, farmer organizations, and development agencies should first identify which commodities experience the greatest losses, which stage generates those losses, and whether the dominant cause is biological deterioration, poor handling, insufficient cooling, inadequate packaging, market congestion, transportation delay, or information failure.

A decentralized market experiencing repeated vegetable spoilage during afternoon heat may benefit from shade, crates, rapid pre-cooling, and a shared solar cold room before adopting advanced digital twins. Another market with adequate cooling but repeated stock expiration may benefit more from shelf-life prediction and inventory prioritization.Loss intelligence should therefore guide investment sequencing.

The second priority should be the development of low-cost shared infrastructure. Solar-powered cooling is particularly relevant in off-grid or unreliable-grid environments because refrigeration otherwise depends on expensive fuels or unstable electricity. Smallholder willingness-to-adopt research indicates considerable interest in these technologies but also confirms that economic capacity and ongoing service costs matter.

The third priority is interoperability. Sensors, cold rooms, market apps, logistics platforms, weighing systems, and farm records should not operate as disconnected technologies. Data should move through simple standardized formats so that product condition can be interpreted alongside location, quantity, storage availability, and market opportunity.

The fourth priority is local-language decision support. A farmer should not need to interpret an LSTM forecast, kinetic deterioration equation, or digital-twin model. The system should communicate the management meaning of the analysis.

The fifth priority is extension support. The Ghana study found substantial willingness to adopt cooling despite low access to post-harvest training and extension services. Training and extension were also associated with technology adoption. Post-harvest intelligence programs should therefore invest in people alongside devices.

The sixth priority is verification through field trials. Many advanced post-harvest studies use laboratory experiments or simulation. Zou and colleagues appropriately identify their reported food-loss reductions as simulation outcomes rather than universal field effects. Future research should test these systems in open markets where temperatures, product varieties, loading practices, traffic delays, power conditions, and user behavior are less controlled.

Field trials should compare intelligence-supported management with existing practice across several market seasons. Measurements should include physical loss, quality loss, selling price, storage duration, energy use, transport cost, labor requirement, system error, technology use, and net financial benefit.

Research should also evaluate whether the additional value is distributed fairly. A traceability or quality platform may benefit wholesalers while farmers bear data-entry costs. Cold storage may reduce spoilage but remain inaccessible to the poorest farmers if pricing is inappropriate. Economic evaluation should therefore examine who pays and who captures the benefits.

Future systems are likely to become increasingly predictive. Instead of warning that spoilage has already begun, they will estimate deterioration risk before it becomes visible. Digital twins, AI, IoT sensors, and shelf-life models are moving in this direction.

The most useful advance, however, may not be higher algorithmic complexity. It may be the integration of biological, market, and logistical time. A product has a remaining biological life, a buyer has a required delivery time, a vehicle has a travel time, and a market has a time-dependent price. Post-harvest intelligence should connect these clocks.

This creates the possibility of predictive decentralized markets. Farmers could receive harvest recommendations based partly on expected demand. Traders could reserve cooling before peak arrivals. Vehicles could prioritize batches with short remaining shelf life. Processors could receive early warnings of temporary surpluses. Market authorities could identify recurring loss hotspots.Such systems would shift post-harvest management from reactive disposal toward preventive coordination.

6. Conclusion

Post-harvest food loss is not simply a storage problem. It is an information, infrastructure, biological, logistical, and market-coordination problem occurring between harvest and consumption. Current FAO data indicate that approximately 13.2% of food is lost globally after harvest and before retail, demonstrating the continuing importance of interventions at these intermediate stages.

Post-harvest intelligence offers a practical framework for improving these decisions. It combines product identity, environmental sensing, quality assessment, remaining-shelf-life prediction, storage availability, logistics, market information, and accessible decision support.Recent evidence demonstrates the technical potential of this approach. Digital twin and artificial-intelligence methods have achieved high temperature-prediction accuracy and modeled meaningful reductions in fruit loss by converting sensor histories into shelf-life intelligence. Smart cold-chain research is similarly shifting from basic condition logging toward predictive product-quality management.

The greatest challenge is making this intelligence relevant to decentralized markets. Small farmers and traders require systems that are affordable, easy to use, capable of operating with imperfect connectivity, and connected with actual physical options such as cooling, transport, packaging, storage, and nearby markets.Evidence from Ghana demonstrates both the severity of the problem and willingness to adopt practical loss-reduction infrastructure. Farmers reported average post-harvest losses of 25%, while 79% expressed willingness to use solar-powered cold storage. Limited access to training and extension, however, demonstrates that technological availability alone is insufficient.Evidence from South African fruit farmers similarly confirms that storage, transportation damage, transpiration, improper handling, and biological deterioration combine to create post-harvest losses. Effective intelligence must therefore remain multidimensional.

The central conclusion is that decentralized markets do not require maximum digitalization. They require the minimum combination of reliable information and practical infrastructure necessary to prevent avoidable deterioration.A successful system should be able to identify the batches most at risk, estimate how much usable life remains, determine which intervention is feasible, and direct products toward markets or processing pathways that can recover the greatest remaining value.
In this sense, post-harvest intelligence is not primarily about sensors or artificial intelligence. It is about making better decisions before food becomes loss.

7. Limitations, Declarations and References

The present study is a conceptual review and does not report original field experiments, laboratory trials, or stakeholder survey data. Quantitative results presented in Graph 1 are taken from the published simulation study of Zou et al. and must not be generalized as universal reductions across all commodities or market conditions.The literature review was structured and evidence-oriented but was not conducted as a formal PRISMA systematic review or meta-analysis. Future work should therefore undertake reproducible multi-database systematic reviews and field validation across different decentralized market systems.

The proposed questionnaire presented in Table 2 has not been administered. Human-participant research using this instrument should obtain applicable institutional ethics approval and informed consent before implementation.Conflict of Interest: The sample author declares no conflict of interest.
Funding: No external funding is reported for preparation of this conceptual review.Ethics Statement: No human or animal participants were directly involved in the present conceptual manuscript.

Data Availability: No original dataset was generated. Quantitative information used in the graph and discussion was obtained from the cited published sources.Author Contribution: The sample authorship details must be replaced with verified author and contributor information before journal publication.

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