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COMMUNICATION

Cold Storage Solutions to Reduce Post-Harvest Loss: Start-ups for Youth in the Agricultural Supply Chain

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ABSTRACT

Post-harvest losses represent a major challenge to global food systems, accounting for up to 30–50% of agricultural output losses, particularly in perishable crops such as fruits, vegetables, dairy, and fish. These losses significantly impact food security, farmer incomes, and national economies—most acutely in developing countries where infrastructure is limited. Cold storage technologies have emerged as one of the most effective solutions to address this issue by preserving the quality and shelf life of perishable produce. In recent years, agritech start-ups, driven by innovative youth entrepreneurs, have been at the forefront of deploying scalable and affordable cold storage solutions, ranging from solar-powered cooling units to mobile refrigeration systems and decentralized storage networks. This communication critically examines the dynamic intersection of cold storage innovations, youth entrepreneurship, and agricultural value chains. It explores the relevance of key theoretical models such as innovation diffusion theory, sustainable livelihoods framework, and supply chain integration theory to understand the adoption and impact of cold storage technologies. Through case studies and evidence from sub-Saharan Africa and South Asia, we highlight how youth-led start-ups are leveraging technology, financing, and digital platforms to bridge critical gaps in agri-logistics. Despite these promising developments, challenges persist, including high capital costs, inconsistent energy supply, inadequate technical

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skills, and weak policy support. As such, this study explores enabling policy frameworks, investment opportunities, and capacity-building strategies necessary for the sustainable deployment of cold storage solutions. Emphasis is placed on the transformative potential of youth-driven innovations in shaping resilient, inclusive, and climate-smart agri-food systems.

Keywords: Agritech; Cold Storage; Food Security; Post-harvest Loss; Start-ups; Youth

1. Introduction

The global food supply system faces profound inefficiencies, particularly in the form of post-harvest losses (PHL), which continue to undermine food security, agricultural profitability, and environmental sustainability. According to the Food and Agriculture Organization [1], nearly 30% of food produced globally is lost or wasted, much of it during the post-harvest stage, before it reaches consumers. These losses are especially acute in perishable crops such as fruits, vegetables, dairy, fish, and meat, which require controlled environments to maintain quality and shelf life [2].

In developing and emerging economies, post-harvest losses can reach up to 40–60% for perishables due to a confluence of factors including inadequate cold chain infrastructure, lack of technical knowledge, insufficient market access, unreliable electricity, and fragmented supply chains [3,4]. These losses not only reduce farmers' incomes but also threaten the food security of millions, placing pressure on natural resources by demanding overproduction to compensate for loss.

Cold storage solutions offer a critical intervention in this context. Cold storage involves maintaining a low-temperature environment for agricultural produce to delay spoilage, reduce microbial activity, and preserve nutritional value [5]. In the absence of such infrastructure, producers—especially smallholder farmers—are forced to sell immediately after harvest, often at low prices due to gluts, thereby exacerbating income volatility and economic vulnerability.

To address these challenges, youth-led agritech start-ups are emerging as key actors in modernizing post-harvest management systems. These entrepreneurial ventures are leveraging innovative technologies such as:

(1) Solar-powered cold rooms (e.g., ColdHubs in Nigeria)

(2) Mobile refrigerated containers for flexible deployment

(3) IoT-enabled temperature and humidity monitoring to ensure optimal conditions

(4) Pay-per-use and shared cold storage models, enhancing affordability

Start-ups like Ecozen, Tan90, and Inficold in India and ColdHubs in Nigeria are pioneering sustainable and scalable models that serve remote and underserved agricultural zones. These technologies are not only helping reduce post-harvest losses but also creating new employment and income opportunities for youth in rural areas, fostering a new wave of "agripreneurs" [6–8].

Importantly, these initiatives are catalyzing a shift in the agricultural value chain-from traditional, subsistence-based practices to technology-driven, market-oriented models. Youth involvement is crucial to this transformation, given their adaptability to technology, entrepreneurial aspirations, and growing engagement with innovation ecosystems supported by government and private incubators.

This communication explores the evolution, design, impact, and scaling challenges of cold storage innovations, with a specific focus on start-ups and youth engagement in the agricultural supply chain. The study synthesizes recent evidence, maps entrepreneurial interventions, and proposes policy recommendations for integrating youth-led innovations into broader food security strategies.

2. Theoretical Framework

This study is anchored on two complementary theoretical perspectives: the Agricultural Innovation Systems (AIS) model and Everett Rogers' Diffusion of Innovations Theory [9]. Together, they provide a robust lens through which to understand how technological, institutional, and entrepreneurial innovations such as cold storage solutions are developed, adopted, and scaled in agricultural contexts-particularly by youth-led start-ups.

2.1. Agricultural Innovation Systems (AIS)

The AIS framework views agricultural innovation as a networked, participatory, and dynamic process rather than a linear transfer of knowledge from research to farmers. It recognizes that multiple actors-including researchers, extension agents, farmers, agribusinesses, financiers, ICT firms, and policymakers-co-create value through interactions. In this system:

Innovation is co-produced through learning, feedback, and adaptation.

Institutions such as incubators, rural innovation hubs, and agritech accelerators play a facilitative role in shaping both formal and informal innovation systems.

Youth start-ups act as change agents that bridge technological gaps in cold storage by introducing affordable, decentralized, and digitally enabled solutions.

This framework is particularly useful in low- and middle-income countries where systemic barriers (e.g., infrastructure gaps, market failures, lack of finance) hinder innovation diffusion. The AIS lens also supports the integration of gender-sensitive and youth-focused innovation policies, making it relevant to inclusive development.

2.2. Diffusion of Innovations Theory

Rogers' theory provides a behavioral understanding of how new technologies-like solar-powered modular cold storage or IoT-enabled cold chain monitoring-are adopted within farming communities. Key concepts include:

(1) Innovators and early adopters (typically start-ups or tech-savvy youth entrepreneurs) serve as role models whose successes reduce uncertainty for the broader community.

(2) The rate of adoption is influenced by five key attributes: relative advantage, compatibility, complexity, trialability, *and* observability.

(3) Social systems, particularly farmer cooperatives and youth networks, influence opinion leadership and community-based uptake.

Applying this theory helps explain why some cold storage solutions (e.g., pay-as-you-store models) are rapidly adopted in certain regions, while others face resistance due to cultural, informational, or affordability constraints.

Together, AIS and Diffusion of Innovations Theory provide an integrated theoretical base to evaluate both the systemic enablers of innovation and the behavioral drivers of technology adoption in youth-driven agricultural transformation.

3. Conceptual Framework

The **conceptual framework** of this study integrates key variables influencing post-harvest loss reduction and maps the pathways through which cold storage innovations, led by youth start-ups, contribute to a sustainable and inclusive agricultural supply chain, as shown in **Figure 1**.

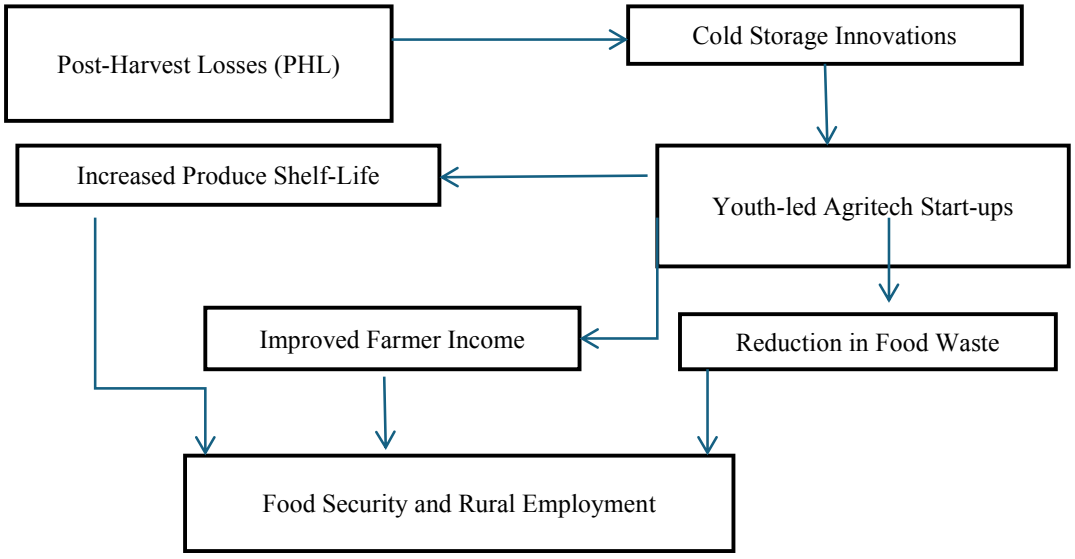

Figure 1. Conceptual Framework.

Key concepts include:

(1) **Post-Harvest Losses (PHL)**: Primarily due to lack of access to cold storage, inefficient logistics, and perishability of produce.

(2) **Cold Storage Solutions**: Innovations such as solar refrigeration, mobile cold hubs, and smart storage monitoring that extend shelf-life and reduce waste.

(3) **Youth Start-ups**: Entrepreneurial ventures led by young innovators applying digital and frugal technologies to address PHL challenges.

(4) **Sustainable Agricultural Supply Chain**: A system characterized by resilience, reduced waste, equitable market access, and environmental sustainability.

This framework emphasizes the interdependence between innovation (cold storage), the agents of change (youth start-ups), and the broader outcomes (sustainability and livelihoods). It also reflects the potential for inclusive rural transformation when technological solutions are embedded within entrepreneurial ecosystems and supported by enabling policies.

4. Research Methodology

This article is based on a systematic review of academic literature, policy reports, and case studies published between 2020–2025. The methodology involved:

(1) **Database**: Google Scholar, Springer, ResearchGate, Frontiers, and Scopus.

(2) **Inclusion Criteria**: Studies focusing on cold storage, youth entrepreneurship, agritech start-ups, and post-harvest logistics.

(3) **Tools**: Textual content analysis, citation mapping, and trend synthesis.

A total of 20 scholarly papers were reviewed to extract evidence-based insights on practical innovations and their socio-economic implications.

5. Results and Discussion

5.1. Scope of Post-Harvest Losses

Post-harvest losses (PHL) represent one of the most critical inefficiencies in global food systems, with fruits and vegetables being the most affected due to their high perishability and sensitivity to temperature fluctuations. According to [4], PHL in horticulture reaches 25–30% in Sub-Saharan Africa, while in South Asia, figures often exceed 40% due to poor infrastructure, especially in rural zones.

In India, Adhya and Sahoo report that over 21 million metric tons of food is lost annually [3], equating to Rs. 92,000 crores (US$12 billion) in economic value. In Nigeria, the absence of cold storage leads to the spoilage of up to 50% of tomatoes harvested, affecting food availability, farmer incomes, and price stability [6]. These losses not only erode profits for producers but also inflate prices for consumers, aggravating food insecurity.

Moreover, food losses contribute to greenhouse gas emissions, with rotting produce emitting methane and wasted agricultural inputs such as water, land, and labor going unutilized [6]. Therefore, minimizing PHL is essential from both an economic and environmental perspective.

5.2. Cold Storage Innovations

Innovative cold storage solutions are emerging as a transformative force in post-harvest logistics, especially in regions where electricity is unreliable or unavailable. Start-ups like:

ColdHubs (Nigeria) deploy solar-powered walk-in cold rooms that can store 2–3 tons of produce and operate on a pay-per-use model [4,8].

Ecozen (India) utilizes thermal energy storage to maintain refrigeration without continuous power, enabling farmers to store perishables longer.

Inficold integrates thermal batteries into existing infrastructure, reducing energy costs and enabling retrofitting of conventional systems [6].

S4S Technologies provides solar dryers for semi-perishables, offering an alternative form of cold chain management.

These innovations have shown a significant impact:

(1) Reduction in spoilage by 60–80%

(2) Increase in farmer income by 30–50% through better price realization

(3) Expansion of market access for rural farmers

(4) Empowerment of women farmers, who often dominate perishable production

Furthermore, digital integration—such as real-time remote monitoring, predictive analytics for shelf life, and

blockchain traceability—enhances transparency and trust in agri-value chains.

5.3. Role of Youth Start-Ups

The involvement of young entrepreneurs in cold chain innovation is central to addressing post-harvest challenges sustainably. Youth bring fresh perspectives, adaptability to digital tools, and willingness to engage with underserved communities. Key innovations from youth-led ventures include:

- IoT-based microcontrollers that track and optimize storage conditions
- Data-driven dashboards to manage inventory and predict spoilage
- Modular and mobile units that can be easily transported between farms and markets

Initiatives like T-Hub, Agri Innovation Centres (AICs), and ICAR-ABI have incubated hundreds of youth-led agri-tech enterprises, offering:

(1) Seed funding

(2) Technical mentorship

(3) Business model validation

(4) Market linkages

As previous studies highlight [9,10], these start-ups are not just technology providers but are transforming into value chain coordinators, linking production with storage, processing, and distribution while creating green jobs in rural areas.

5.4. Policy and Investment Ecosystem

Several policy frameworks and programs have emerged globally to support cold chain development and youth engagement:

India's Startup India and PM-FME schemes provide tax relief, loans, and technical assistance for food processing and cold storage ventures.

The African Development Bank's ENABLE Youth Program aims to empower 8 million African youth to become agri-entrepreneurs by investing in cold chains, logistics, and processing units [5].

The FAO-supported AgrInvest program facilitates private investment in agri-food systems, especially for post-harvest infrastructure.

One District One Product (ODOP) and Agri Infrastructure Fund (AIF) in India promote district-specific post-harvest infrastructure through public-private partnerships (PPPs) [11].

Moreover, impact investors and venture capitalists are showing growing interest in "climate-smart" agri-logistics, with cold chain start-ups attracting funding rounds from entities like Omnivore, Acumen, and USAID-backed funds.

5.5. Challenges and Constraints

Despite promising innovations, youth-led cold storage start-ups face significant barriers to scalability and impact:

(1) Capital Access

Many start-ups lack the collateral and credit history required to access formal finance. Venture capital is often risk-averse in agriculture due to perceived uncertainties in yield, seasonality, and policy volatility. Moreover, financing models rarely align with the cash flow cycles of smallholder farming [12].

(2) Energy Costs and Technology Affordability

Conventional cold storage systems are electricity-intensive, and rural electrification remains inconsistent. Even solar solutions require high upfront capital investment, making them unaffordable for low-income producers unless subsidized or shared via cooperatives.

(3) Logistical and Infrastructure Gaps

Poor rural road connectivity, lack of aggregators, and absence of transport refrigeration limit the efficacy of cold storage. Storage alone is insufficient unless linked with efficient transport, digital marketplaces, and processing facilities.

(4) Knowledge and Skills Gaps

Youth often lack technical skills in refrigeration, HVAC systems, and agri-logistics. Capacity-building in these domains remains limited, constraining technology management and maintenance.

(5) Gender Barriers

While women play a major role in perishable value chains, gender-blind policies and lack of tailored financial products often exclude them from cold storage innovations and entrepreneurship.

Together, these findings underscore the critical role

of youth-led, technology-driven, policy-enabled solutions in addressing the post-harvest loss crisis. Cold storage innovations must be embedded within systems thinking that combines infrastructure, finance, skills, and inclusive business models.

6. Conclusions, Policy Implications and Recommendations

Post-harvest losses continue to pose a severe threat to food security, farmer livelihoods, and sustainable agriculture across much of the Global South. With fruits, vegetables, dairy, fish, and other perishables experiencing spoilage rates of up to 30–50% in many developing regions, the need for efficient and accessible cold storage infrastructure has never been more urgent. The research reviewed in this article clearly indicates that cold storage technologies—especially those designed and deployed by youth-led start-ups—offer transformative potential in addressing these challenges.

The evolution of solar-powered cold rooms, IoT-integrated refrigeration systems, and mobile cold hubs represents a leap forward from conventional storage models. These innovations are not only reducing food waste and increasing farmers' incomes but also stimulating rural entrepreneurship, creating jobs, and strengthening agri-value chains. Youth entrepreneurs, supported by incubators and policy ecosystems, have emerged as key actors in this transformation. Their agility, digital literacy, and community ties enable them to craft context-specific, affordable solutions tailored to the needs of smallholder farmers.

However, the impact of these innovations is constrained by persistent challenges such as limited access to finance, unreliable energy infrastructure, inadequate rural logistics, and skill shortages. Unless addressed holistically, these barriers may continue to hinder the scalability and sustainability of youth-driven cold storage solutions.

Ultimately, reducing post-harvest losses is not merely a technical issue but a systemic development imperative. It intersects with nutrition security, climate resilience, inclusive growth, and sustainable food systems. Cold storage innovation, when coupled with enabling policies, targeted investments, and inclusive training programs, can catalyze a profound shift in how agricultural produce is managed post-harvest.

This communication concludes that the future of cold storage in agriculture lies at the intersection of technology, youth empowerment, and collaborative ecosystems. Investing in this nexus is essential not just for mitigating post-harvest losses, but for building a more resilient, equitable, and food-secure world.

6.1. Policy Implications and Recommendations

The evidence presented in this communication highlights that youth-led cold storage solutions are pivotal to reducing post-harvest losses and fostering innovation in the agricultural supply chain. However, for these technologies and enterprises to scale sustainably, they must be embedded within an enabling ecosystem supported by targeted policy interventions, strategic investments, and institutional collaboration. The following policy implications and recommendations are proposed:

6.1.1. Policy Implications

(1) Mainstreaming Cold Chain in National Food Security Policy

Cold storage should be recognized as a critical pillar of national food security, not just a commercial add-on. Policies should formally integrate cold chain infrastructure development in rural development, climate resilience, and nutrition strategies.

(2) Youth Entrepreneurship as a Development Priority

Governments and international agencies must recognize youth agripreneurship in cold chain innovation as a core strategy for job creation and agricultural modernization. This involves developing customized schemes that provide easier access to capital, land, and markets for young innovators.

(3) Public-Private Partnerships (PPPs) for Infrastructure Expansion

The cold chain sector benefits from economies of scale. Thus, PPP models involving governments, start-ups, cooperatives, and private investors are essential to ensure affordability and reach in rural and remote regions.

(4) Climate-Smart Investment Focus

Given that refrigeration is energy-intensive, support must prioritize solar-powered and energy-efficient cold

storage technologies as part of national climate action plans, green economy strategies, and SDG targets.

6.1.2. Strategic Recommendations

(1) Establish Cold Storage Innovation Grants and Financing Windows

Design and operationalize special financing instruments, such as:

- De-risked loans and credit guarantees
- Matching grants for equipment and prototyping
- Microleasing models for smallholders

This will make cold chain adoption viable for both youth entrepreneurs and farmer groups.

(2) Strengthen Youth-Centric Agri-Incubators

Scale up and replicate successful incubators such as ICAR-ABI, T-Hub, and ENABLE Youth across rural areas. These platforms should:

- Offer technical training on cold chain design and maintenance
- Provide mentorship on business development
- Facilitate peer learning networks for young agripreneurs

(3) Incentivize Decentralized, Modular Cold Chain Systems

Subsidize or incentivize start-ups deploying decentralized, solar-powered cold hubs in rural regions. Promote mobile cold rooms and shared storage platforms (e.g., community-based models), especially in high-loss horticultural zones.

(4) Integrate Cold Chain Training into Agricultural Education

Reform agricultural training institutions and vocational schools to include:

- Cold chain engineering
- Refrigeration maintenance
- Agribusiness entrepreneurship

This will create a pipeline of skilled youth capable of running and sustaining cold storage operations.

(5) Facilitate Market Linkages and Digital Integration

Develop policies that link cold storage networks with:

- Digital agricultural platforms
- E-commerce and logistics services
- Blockchain traceability tools

This enhances price transparency, reduces waste, and connects rural producers with high-value markets.

(6) Gender-Inclusive Policies

Design policies and funding instruments that prioritize women-led start-ups and women farmer groups in cold chain projects. Provide tailored training, subsidies, and digital tools for female entrepreneurs in the perishable supply chain.

(7) Monitoring and Evaluation Frameworks

Implement robust M&E systems to track:

- Reduction in post-harvest loss (by crop and region)
- Return on investment from youth-led cold storage models
- Carbon savings and energy efficiency of deployed units

This data should inform future scaling and public procurement decisions.

By implementing these recommendations, governments and development partners can create an ecosystem where youth innovation in cold storage becomes a key driver of agricultural transformation, rural employment, and food system resilience.

Author Contributions

Conceptualization, S.M.S. and I.P.S.; methodology, M.M.A.; software, S.M.S.; validation, I.P.S., M.M.A. and B.S.S.; formal analysis, S.M.S.; investigation, B.S.S.; resources, S.M.S.; data curation, I.P.S.; writing—original draft preparation, S.M.S.; writing—review and editing, I.P.S. and M.M.A.; visualization, B.S.S.; supervision, S.M.S.; project administration, S.M.S., I.P.S. and B.S.S. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

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