International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
| An ISO 9001:2015 Certified Journal |

Reduction of Post-harvest Losses Using Cold storage and EV-Based Refrigerated Transportation in the Indore Region

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ABSTRACT
Post-harvest losses remain a major challenge in the agricultural sector of the Indore region, leading to reduced farmer income, food wastage, and supply chain inefficiencies. Inadequate cold storage facilities and dependence on conventional diesel-powered transportation contribute significantly to the deterioration of perishable commodities such as fruits, vegetables, and dairy products. This study examines the potential of integrating cold storage infrastructure with Electric Vehicle (EV)-based refrigerated transportation as a sustainable solution for reducing post-harvest losses. The proposed system ensures temperature-controlled storage and transportation, thereby preserving product quality, extending shelf life, and minimizing spoilage. Additionally, EV-based refrigerated vehicles help reduce greenhouse gas emissions, fuel consumption, and environmental pollution associated with conventional cold-chain logistics. The study highlights the economic, environmental, and operational benefits of an integrated cold-chain network in the Indore region. It concludes that adopting cold storage and EV-based refrigerated transportation can enhance food security, improve farmer livelihoods, and support sustainable agricultural development.

Keywords: Post-harvest losses, Cold Storage, Electric Vehicles (EVs), Refrigerated Transportation, Cold Chain Logistics, Sustainable Agriculture, Indore Region.

1. INTRODUCTION
Post-harvest losses remain a pressing concern in agricultural regions like Indore, where inadequate cold storage facilities and inefficient transportation networks lead to significant deterioration of perishable commodities. Conventional refrigerated vehicles, powered by fossil fuels, contribute heavily to pollution, worsening environmental conditions while failing to adequately preserve harvested produce. The absence of reliable cold storage infrastructure accelerates spoilage during post-harvest handling, reducing farmer incomes and threatening food security. Adopting EV-based refrigerated transportation integrated with advanced cold storage systems presents a sustainable pathway — simultaneously curtailing post-harvest losses, minimizing pollution, and strengthening the agricultural supply chain in the Indore region.

2. BACKGROUND
India ranks among the world's largest agricultural producers, yet loses approximately 16–18% of its total food production due to inadequate post-harvest management. The Indore region, a significant agricultural hub in Madhya Pradesh, faces persistent challenges in preserving perishable commodities such as fruits, vegetables, and dairy products following harvest.

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Cold storage infrastructure in semi-urban and rural areas remains grossly underdeveloped, leaving farmers dependent on traditional, unregulated storage methods that accelerate spoilage. The lack of temperature-controlled environments during storage and transportation creates a critical gap between farm production and market delivery, resulting in massive economic losses for smallholder farmers.

Conventional refrigerated transportation systems, predominantly diesel-powered, further compound the problem by contributing significantly to vehicular pollution. In a rapidly urbanizing region like Indore, rising emissions from freight and cold-chain logistics have intensified air quality concerns, conflicting with national sustainability goals outlined under India's climate commitments and the National Action Plan on Climate Change (NAPCC).

Globally, the transition toward electric vehicle (EV)-based transportation has gained momentum as a viable strategy for reducing carbon footprints in logistics. When combined with modernized cold storage facilities powered by renewable energy, EV refrigerated vehicles offer a dual advantage — preserving post-harvest produce integrity while drastically reducing pollution levels.

Recognizing these converging challenges, this study investigates the potential of integrating cold storage infrastructure with EV-based refrigerated transportation in the Indore region as a comprehensive solution to reduce post-harvest losses, enhance farmer livelihoods, and promote environmentally responsible agricultural supply chain management.

3. CHALLENGES IN DETAIL

1. Post-harvest Losses and Inadequate Cold storage Infrastructure

One of the most significant challenges in the Indore region is the severe shortage of functional cold storage facilities at the farm and village level. Most smallholder farmers lack access to pre-cooling units or temperature-controlled storage immediately after harvest, which is the most critical period for perishable commodities. The gap between harvest and storage leads to rapid microbial growth, moisture loss, and physical deterioration. Existing cold storage units in the region are largely centralized, located in urban areas, making them inaccessible to rural farmers due to distance and high operational costs. Furthermore, frequent power outages in semi-urban and rural zones disrupt temperature maintenance, rendering even available cold storage facilities unreliable. Seasonal demand surges — particularly during peak harvest periods — overwhelm existing storage capacity, leaving large volumes of produce unprotected and vulnerable to post-harvest spoilage.

2. Inefficient and Polluting Transportation Networks

The transportation of perishable agricultural produce in the Indore region relies heavily on conventional, non-refrigerated vehicles or aging diesel-powered refrigerated trucks. These vehicles are ill-equipped to maintain consistent temperature zones required for sensitive commodities during transit. Poor road connectivity between rural farms and urban markets extends transportation time, increasing exposure to ambient temperatures and accelerating spoilage. Diesel-based refrigerated vehicles not only consume high quantities of fuel but also emit significant levels of CO_2, NO_x, and particulate matter, contributing to vehicular pollution along major freight corridors. The high operational and maintenance costs of conventional refrigerated transportation discourage small and medium-scale traders from investing in cold-chain logistics, widening the gap in temperature-controlled delivery systems.

3. Environmental Pollution from Cold-Chain Operations

Conventional cold storage facilities in India, including those in the Indore region, predominantly rely on hydrochlorofluorocarbon (HCFC)-based refrigerants such as R-22, which are known ozone-depleting substances contributing to greenhouse gas emissions. Diesel generator sets used as backup power for cold storage during electricity failures emit substantial quantities of harmful gases, exacerbating local air pollution. Combined with emissions from diesel refrigerated vehicles used in transportation, the overall carbon footprint of the existing cold-chain system is considerably high. This environmental burden directly contradicts India's commitments under the Paris Agreement and the Kigali Amendment to phase down harmful refrigerants and reduce agricultural sector emissions.

4. Economic and Financial Barriers

The high capital investment required for establishing modern cold storage infrastructure and procuring EV-based refrigerated vehicles poses a substantial financial challenge, particularly for small-scale farmers and agribusiness entrepreneurs in the Indore region. Limited access to institutional credit, lack of government subsidy awareness, and absence of viable business models for cold storage operations in rural areas deter private investment. Post-harvest losses translate directly into reduced farm incomes, creating a vicious cycle where financially constrained farmers cannot afford the very infrastructure needed to protect their produce. The high upfront cost of electric refrigerated vehicles, despite lower long-term operational expenses, remains a significant deterrent for logistics operators accustomed to conventional transportation economics.

5. Technological and Awareness Gaps

A considerable challenge lies in the limited awareness among farmers, traders, and logistics operators regarding best practices in post-harvest handling, cold storage management, and the benefits of EV-based transportation. Many farmers in the Indore region continue to use traditional harvesting and storage methods due to lack of technical knowledge and training. The absence of real-time temperature monitoring systems within cold storage units and refrigerated vehicles results in undetected temperature fluctuations that silently accelerate produce deterioration. Limited integration of digital technologies such as IoT-based cold-chain monitoring, GPS-enabled transportation tracking, and data-driven inventory management further weakens the efficiency of the existing post-harvest supply chain.

6. Policy and Institutional Challenges

Despite several government schemes such as the Pradhan Mantri Kisan Sampada Yojana (PMKSY) and the National Horticulture Mission aimed at strengthening cold storage infrastructure and reducing post-harvest losses, implementation gaps persist at the ground level in regions like Indore. Fragmented coordination among agricultural departments, transportation authorities, pollution control boards, and energy agencies results in disjointed policy execution. Regulatory frameworks governing EV adoption in commercial freight transportation are still evolving, creating uncertainty for investors and fleet operators.

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Additionally, the lack of standardized quality protocols for **post-harvest** handling and cold storage operations across the supply chain undermines the consistency and reliability of produce reaching end markets.

4. IMPORTANCE OF REDUCING POST-HARVEST LOSSES USING COLD STORAGE AND EV-BASED REFRIGERATED TRANSPORTATION IN THE INDORE REGION

1. Enhancing Food Security

Reducing post-harvest losses is fundamentally linked to strengthening food security at local, regional, and national levels. In the Indore region, where agriculture supports a significant proportion of the population, every percentage reduction in post-harvest spoilage directly translates into greater availability of nutritious food for consumers. Modernized cold storage infrastructure ensures that harvested produce retains its nutritional quality, freshness, and shelf life from farm to fork. By minimizing wastage through temperature-controlled transportation and storage, a larger volume of food reaches end consumers, contributing meaningfully to India's goal of achieving zero hunger as outlined under the United Nations Sustainable Development Goals (SDGs).

2. Improving Farmer Incomes and Livelihoods

One of the most direct and tangible benefits of reducing post-harvest losses is the improvement in farmer incomes. Smallholder farmers in the Indore region often incur devastating financial losses due to spoilage occurring between harvest and market delivery. Access to reliable cold storage facilities allows farmers to store their produce strategically, avoiding forced distress sales during peak harvest periods when market prices are lowest. By timing their market entry when prices are favorable, farmers can significantly enhance their profit margins. Furthermore, EV-based refrigerated transportation ensures that produce arrives at markets in premium condition, commanding higher prices and strengthening farmer bargaining power within the agricultural value chain.

3. Reducing Environmental Pollution

The transition from conventional diesel-powered refrigerated vehicles to EV-based refrigerated transportation holds immense environmental importance for the Indore region. Diesel vehicles are major contributors to vehicular pollution, releasing harmful greenhouse gases including CO_2, NO_x, and particulate matter that degrade air quality and accelerate climate change. Electric refrigerated vehicles produce zero direct tailpipe emissions, significantly reducing the pollution burden associated with cold-chain logistics. When powered by renewable energy sources, EV-based transportation achieves near-zero carbon operations. Additionally, upgrading cold storage facilities to use environmentally friendly refrigerants and energy-efficient systems further reduces the ecological footprint of post-harvest infrastructure, aligning regional agricultural practices with national and global climate commitments.

4. Strengthening Agricultural Supply Chain Efficiency

Integrating modern cold storage with EV-based refrigerated transportation significantly enhances the overall efficiency of the agricultural supply chain in the Indore region. A well-functioning cold chain minimizes temperature fluctuations during post-harvest handling,

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storage, and transit, ensuring consistent produce quality across the supply network. Reduced spoilage rates lower the cost of waste management and enable more predictable supply flows to urban markets, processing units, and export hubs. Improved supply chain efficiency also benefits downstream stakeholders — including wholesalers, retailers, and food processors — by providing them with higher-quality, longer-lasting raw materials, ultimately reducing food system inefficiencies across the entire value chain.

5. Supporting Economic Growth and Employment Generation

The development of cold storage infrastructure and EV-based refrigerated transportation networks creates significant economic opportunities in the Indore region. Establishing and operating modern cold storage facilities generates direct employment for technicians, managers, and support staff, while also stimulating demand in ancillary industries such as construction, refrigeration technology, and renewable energy. The growth of EV-based cold-chain logistics creates new business opportunities for entrepreneurs, fleet operators, and technology service providers. Reduced post-harvest losses at the farm level release financial resources that farmers can reinvest in productivity-enhancing inputs, further driving agricultural economic growth and rural development across the region.

6. Promoting Sustainable Agricultural Development

The importance of combining cold storage improvements with EV-based transportation extends beyond immediate economic and environmental benefits — it represents a paradigm shift toward sustainable agricultural development in the Indore region. By simultaneously addressing post-harvest inefficiencies and pollution from logistics operations, this integrated approach aligns regional agricultural practices with the principles of circular economy and green growth. Sustainable cold-chain systems reduce resource wastage, lower energy consumption through efficient technologies, and minimize the environmental degradation associated with conventional post-harvest handling. This sustainability dimension is increasingly important as climate change threatens agricultural productivity, making resilient and low-carbon food systems an essential priority for the region's long-term development.

7. Advancing Technological Innovation and Digital Integration

The importance of modernizing post-harvest infrastructure also lies in its potential to catalyze broader technological advancement in the Indore region's agricultural sector. Implementing smart cold storage systems equipped with IoT-based temperature and humidity sensors enables real-time monitoring and proactive management of storage conditions, preventing undetected spoilage. GPS-enabled EV refrigerated transportation allows logistics operators to track vehicle locations, monitor cargo temperatures remotely, and optimize delivery routes for maximum efficiency. This digital integration of cold storage and transportation infrastructure creates a data-rich ecosystem that supports evidence-based decision-making, enhances supply chain transparency, and positions the Indore region as a model for technology-driven, sustainable post-harvest management in India.

8. Aligning with National Policy Goals and Government Initiatives

The importance of this initiative is further reinforced by its alignment with several key national policy frameworks and government programs. Schemes such as the Pradhan Mantri Kisan

Sampada Yojana (PMKSY), the National Horticulture Mission, and the FAME India Scheme (Faster Adoption and Manufacturing of Electric Vehicles) collectively support investments in cold storage infrastructure, post-harvest management, and EV-based transportation respectively. Leveraging these policy frameworks, the Indore region stands to benefit from financial incentives, technical assistance, and institutional support for building an integrated cold-chain ecosystem. Reducing agricultural pollution through cleaner transportation also supports India's Nationally Determined Contributions (NDCs) under the Paris Agreement, demonstrating that regional agricultural innovation can contribute meaningfully to national climate goals.

5. FUTURE SCOPE OF REDUCING POST-HARVEST LOSSES USING COLD STORAGE AND EV-BASED REFRIGERATED TRANSPORTATION IN THE INDORE REGION

1. Expansion of Decentralized Cold storage Networks

The future scope of cold storage development in the Indore region lies significantly in the expansion of decentralized, community-level storage infrastructure. Rather than relying solely on large centralized cold storage facilities, future strategies can focus on establishing small-scale, solar-powered cold storage units at village and panchayat levels, bringing temperature-controlled preservation directly to the farm gate. Advances in modular cold storage technology allow for scalable, low-cost units that can be deployed rapidly across rural areas. Future policy frameworks can incentivize cooperative cold storage ownership models, enabling groups of smallholder farmers to collectively invest in and manage shared facilities, dramatically reducing individual financial burdens while maximizing post-harvest protection across wider geographic areas.

2. Widespread Adoption of EV-Based Refrigerated Transportation

The future of cold-chain logistics in the Indore region is increasingly oriented toward full-scale adoption of EV-based refrigerated transportation. As battery technology continues to advance, electric refrigerated vehicles will achieve greater driving ranges, faster charging times, and higher payload capacities, making them increasingly viable for long-distance agricultural freight. The declining cost trajectory of lithium-ion batteries and the anticipated introduction of solid-state battery technology will further reduce the upfront cost of EV refrigerated fleets, accelerating adoption among small and medium logistics operators. Future integration of vehicle-to-grid (V2G) technology will allow EV refrigerated trucks to feed surplus energy back into the grid during non-operational hours, transforming the transportation fleet into a distributed energy resource that supports regional power stability.

3. Integration of Renewable Energy with Cold storage Operations

A critical dimension of future cold storage development involves the deep integration of renewable energy sources — particularly solar and wind power — into storage facility operations. Solar-powered cold storage units equipped with advanced battery storage systems can operate independently of the conventional electricity grid, eliminating vulnerability to power outages that currently compromise post-harvest preservation in the Indore region. Future cold storage facilities can incorporate hybrid energy systems combining solar panels, wind turbines, and battery banks to ensure uninterrupted, zero-pollution operations throughout the year. Green hydrogen-powered refrigeration systems represent an emerging future technology with significant potential for large-scale cold storage applications, offering a completely clean energy pathway for **post-harvest** infrastructure development.

4. Smart and IoT-Enabled Cold Chain Management

The future scope of **post-harvest** management in the Indore region encompasses the widespread deployment of smart, Internet of Things (IoT)-enabled technologies across the entire cold chain. Future cold storage facilities will be equipped with advanced sensor networks continuously monitoring temperature, humidity, ethylene levels, and CO_2 concentrations in real time, enabling automated adjustments that optimize preservation conditions for different commodity types. AI-powered predictive analytics will allow cold storage operators to anticipate equipment failures, demand fluctuations, and optimal storage durations, minimizing both spoilage and energy wastage. Smart EV-based transportation systems will utilize machine learning algorithms to optimize delivery routes, predict maintenance requirements, and dynamically adjust refrigeration settings based on cargo type and ambient conditions, creating a fully intelligent, responsive cold-chain ecosystem that drastically reduces post-harvest losses.

5. Blockchain-Based Supply Chain Transparency

Future post-harvest management systems in the Indore region can leverage blockchain technology to create fully transparent, tamper-proof records of produce movement from farm to consumer. Each stage of the cold chain — including harvesting, cold storage entry and exit, refrigerated transportation dispatch and delivery — can be recorded on an immutable blockchain ledger, providing all supply chain stakeholders with verifiable data on produce quality, temperature history, and handling conditions. This transparency will enhance consumer confidence in food safety, enable rapid traceability during contamination events, and support premium market positioning for certified, cold-chain-managed produce from the Indore region. Blockchain integration also facilitates fair and transparent payment systems for farmers, reducing exploitation by intermediaries and ensuring equitable value distribution across the agricultural supply chain.

6. Development of Green Cold-Chain Corridors

A transformative future scope lies in the development of dedicated green cold-chain corridors connecting major agricultural production zones in the Indore region to urban consumption centers, processing hubs, and export terminals. These corridors would feature strategically located EV charging infrastructure, solar-powered cold storage relay stations, and smart traffic management systems optimized for refrigerated freight transportation. Green cold-chain corridors would minimize transportation time and temperature exposure for perishable commodities, significantly reducing post-harvest losses during transit. Future expansion of these corridors beyond the Indore region — linking to other major agricultural hubs in Madhya Pradesh and neighboring states — would create an integrated, low-pollution cold-chain network capable of transforming regional and national agricultural supply chain performance.

7. Climate-Resilient Post-harvest Infrastructure

As climate change increasingly disrupts agricultural production patterns in central India, the future scope of post-harvest management must incorporate climate resilience as a core design principle. Future cold storage facilities in the Indore region will need to be engineered to withstand extreme heat events, flooding, and irregular power availability resulting from climate variability. Advanced building materials with superior thermal insulation properties, passive cooling design principles, and climate-adaptive refrigeration systems will form the foundation of next-generation cold storage infrastructure. EV-based refrigerated transportation fleets will require battery systems capable of maintaining performance across a wider range of ambient temperatures, ensuring reliable cold-chain transportation even during extreme weather conditions that are projected to become more frequent in the region.

8. Integration with Export Markets and Global Value Chains

The future scope of cold storage and EV-based transportation development in the Indore region extends to the integration of local agricultural produce into national and global export value chains. With enhanced post-harvest preservation capabilities, produce from the Indore region can meet the stringent quality and safety standards required by international markets in Europe, the Middle East, Southeast Asia, and beyond. Future development of export-grade cold storage facilities and internationally certified refrigerated transportation fleets will position Indore as a significant node in global agricultural trade networks. Reduced post-harvest losses combined with lower pollution credentials from EV-based cold chains will enhance the sustainability profile of Indore's agricultural exports, attracting premium buyers increasingly prioritizing environmentally responsible supply chains.

9. Policy Innovation and Regulatory Advancement

The future scope also encompasses significant evolution in policy frameworks governing cold storage infrastructure, EV transportation, and post-harvest management in India. Future regulatory advancements may include mandatory cold-chain standards for perishable commodity transportation, financial incentives specifically targeting solar-powered cold storage development in rural areas, and accelerated EV adoption mandates for agricultural freight transportation to reduce pollution. Carbon credit mechanisms could be developed to reward cold-chain operators who demonstrably reduce pollution through renewable energy adoption and EV transportation use, creating new revenue streams that improve the financial viability of sustainable post-harvest infrastructure. Strengthened public-private partnership models will attract greater private investment into cold storage and EV logistics infrastructure, accelerating the pace of cold-chain development across the Indore region.

10. Capacity Building and Human Resource Development

The long-term success of advanced cold storage and EV-based transportation systems in the Indore region depends critically on the development of a skilled human resource base capable of operating, maintaining, and innovating within modern cold-chain ecosystems. Future scope includes the establishment of specialized training institutes and certification programs focused on cold storage technology, EV maintenance, post-harvest handling best practices, and cold-chain logistics management. Agricultural universities and technical institutions in Madhya

Pradesh can develop dedicated curricula integrating post-harvest science, refrigeration engineering, EV technology, and sustainable transportation management. Community-level awareness programs targeting farmers, self-help groups, and rural entrepreneurs will build grassroots capacity for adopting and sustaining cold storage and EV transportation solutions, ensuring that the benefits of technological advancement are equitably distributed across the Indore region's agricultural communities.

6. LITERATURE REVIEW (2022–2026)

1. Food and Agriculture Organization (FAO) Report (2022)

The Food and Agriculture Organization highlighted that nearly one-third of food produced globally is lost before reaching consumers, with post-harvest losses being particularly severe in developing countries. The report emphasized the importance of cold storage infrastructure and temperature-controlled transportation in reducing spoilage and improving food security. It further recommended investments in sustainable cold-chain systems to support agricultural productivity and farmer income.

2. National Centre for Cold Chain Development (NCCD) Report (2023)

The NCCD reported that inadequate cold storage capacity and inefficient logistics continue to be major contributors to post-harvest losses in India. The report stressed the need for decentralized cold storage facilities at the village level and recommended integrating renewable energy technologies to improve the reliability and sustainability of cold-chain operations.

3. Sharma and Gupta (2023)

Sharma and Gupta examined the role of cold-chain infrastructure in reducing agricultural wastage in central India. Their findings revealed that modern cold storage systems can reduce spoilage of fruits and vegetables by up to 35% while improving product quality and market value. The study also highlighted the importance of temperature monitoring systems for maintaining produce freshness.

4. Kumar et al. (2024)

Kumar and colleagues investigated the feasibility of Electric Vehicle (EV)-based refrigerated transportation for agricultural logistics. The study concluded that EV refrigerated vehicles significantly reduce fuel costs and greenhouse gas emissions compared to conventional diesel-powered refrigerated trucks. The researchers suggested that EV adoption can contribute to sustainable agricultural supply chains while maintaining product quality during transit.

5. Singh et al. (2024)

Singh and co-researchers explored the integration of solar-powered cold storage facilities with refrigerated transportation networks. The study demonstrated that renewable energy-powered cold storage units improve energy efficiency and reduce operational costs. The authors recommended adopting decentralized solar cold storage systems in rural agricultural regions to minimize post-harvest losses.

6. International Energy Agency (IEA) Report (2024)

The IEA reported rapid growth in electric mobility worldwide, highlighting the increasing adoption of EVs in freight and logistics sectors. The report identified refrigerated transport as a promising application area for electric commercial vehicles due to their lower emissions and reduced operating costs. The study emphasized that combining EV logistics with renewable energy infrastructure can accelerate decarbonization of agricultural supply chains.

7. Patel and Verma (2025)

Patel and Verma studied smart cold-chain management systems using IoT-enabled sensors for monitoring temperature and humidity. Their findings indicated that real-time monitoring can reduce produce spoilage by ensuring optimal storage conditions throughout the supply chain. The study recommended integrating digital technologies with cold storage and refrigerated transportation systems.

8. Recent Research on EV Refrigerated Transportation **(2025)**

Several recent studies have focused on battery-powered refrigerated vehicles for transporting perishable agricultural products. These studies found that EV-based refrigeration systems can maintain stable temperature conditions while reducing carbon emissions by more than 60% compared to conventional diesel vehicles. Researchers also highlighted the potential of solar-assisted charging systems for extending operational efficiency.

9. Green Cold Chain and Sustainable Logistics Studies (2026)

Emerging studies in 2026 emphasize the development of green cold-chain corridors combining renewable energy-powered cold storage, EV-based transportation, and digital monitoring systems. Researchers found that integrated cold-chain ecosystems significantly improve supply chain efficiency, reduce food wastage, and support climate-resilient agricultural development. These studies identify sustainable cold-chain infrastructure as a critical component of future agricultural modernization.

7. RESEARCH GAP

The reviewed literature demonstrates significant progress in cold storage technologies, renewable energy integration, smart monitoring systems, and EV-based refrigerated transportation. However, most studies focus on these components individually or at a national level. Limited research has examined the combined impact of decentralized cold storage facilities and EV-based refrigerated transportation on post-harvest loss reduction in the Indore region of Madhya Pradesh. Furthermore, there is insufficient empirical evidence regarding their potential effects on farmer income, carbon emission reduction, and supply chain efficiency. Therefore, the present study seeks to address this gap by evaluating an integrated, sustainable cold-chain model tailored to the agricultural conditions of the Indore region.

Conceptual Framework (148 words)

The conceptual framework for this study illustrates the interrelationships between key variables aimed at reducing post-harvest losses in the Indore region.

Independent Variables:

- Development of modern cold storage infrastructure (decentralized, solar-powered units)
- Adoption of Electric Vehicle (EV)-based refrigerated transportation

Dependent Variable:

- Reduction in Post-Harvest Losses (measured through spoilage rate, shelf life extension, and quality retention of perishable commodities)

Mediating Variables:

- Maintenance of optimal temperature and humidity throughout the supply chain
- Reduction in environmental pollution and operational costs
- Improvement in supply chain efficiency and market accessibility

Moderating Variables:

- Government policies and subsidies, technological integration (IoT, blockchain), and farmer awareness levels.

The framework posits that the integration of cold storage and EV-based refrigerated transportation creates a robust, sustainable cold-chain ecosystem. This synergy is expected to minimize spoilage, enhance farmer incomes, reduce carbon emissions, and strengthen food security in the Indore region. The model is grounded in the farm-to-market continuum, emphasizing both economic and environmental sustainability.

Hypothesis

H_1: Implementation of decentralized cold storage facilities and EV-based refrigerated transportation will reduce post-harvest losses of perishable produce by at least 25–40% in the Indore region.

H_2: The use of EV-based refrigerated vehicles integrated with renewable energy-powered cold storage will significantly lower carbon emissions (CO_2, NO_x) from cold-chain logistics and increase net farmer income through reduced spoilage and better price realization in the Indore region.

8. OBJECTIVE OF THE STUDY

Specific Objectives:

1. To examine the current extent of post-harvest losses in fruits, vegetables, and dairy products in the Indore region and identify the major gaps in existing cold storage and transportation infrastructure.

2. To evaluate the potential impact of decentralized cold storage facilities and EV-based refrigerated transportation on reducing post-harvest losses by at least 25–40% and extending the shelf life of perishable produce.

3. To analyse the environmental benefits of the proposed system, particularly the reduction in greenhouse gas emissions (CO_2 and NO_x) through the adoption of renewable energy-powered cold storage and EV-based refrigerated vehicles.

4. To assess the socio-economic impact of the integrated cold chain system on farmer incomes, supply chain efficiency, and overall livelihood improvement in the Indore region.

9. RESEARCH METHODOLOGY

9.1 Research Design This study adopts a **mixed-methods research design** with a predominant focus on exploratory and descriptive approaches. The research combines both quantitative and qualitative methods to comprehensively analyze the potential of integrating decentralized cold storage facilities with EV-based refrigerated transportation for reducing post-harvest losses in the Indore region. The exploratory design helps in understanding the existing challenges, while the descriptive design evaluates the possible impact of the proposed system.

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9.2 Study Area The study is conducted in the Indore region of Madhya Pradesh, India. Indore district and its surrounding rural areas, which are major producers of fruits, vegetables, and dairy products, have been selected purposively due to high agricultural production coupled with significant post-harvest losses.

9.3 Population and Sampling The target population includes smallholder farmers, cold storage operators, logistics service providers, and agricultural traders in the Indore region. A **multi-stage sampling technique** will be used:

- Random selection of 4 tehsils/blocks from Indore district.
- From each selected block, 3–4 villages will be chosen.
- A sample size of **200 smallholder farmers** and **40 stakeholders** (traders, transporters, and officials) will be selected using stratified random sampling for quantitative data. For qualitative insights, **20 Key Informant Interviews (KIIs)** and **4 Focus Group Discussions (FGDs)** will be conducted.

9.4 Data Collection Methods

Primary Data:

- Structured questionnaires and interview schedules for farmers and stakeholders.
- Focus Group Discussions (FGDs) with farmer groups.
- Key Informant Interviews with agriculture officers, cold chain experts, and EV logistics operators.
- Field observations of existing cold storage units and transportation practices.

Secondary Data:

- Reports from National Centre for Cold Chain Development (NCCD), Ministry of Agriculture, MP State Horticulture Department, and FAO.
- Research papers, government schemes (PMKSY, FAME India), and statistical data from Indore District Statistical Handbook.

9.5 Data Analysis

- **Quantitative Data:** Analyzed using Statistical Package for Social Sciences (SPSS) and MS Excel. Descriptive statistics (mean, percentage, frequency), correlation analysis, and regression analysis will be applied to test the hypotheses.
- **Qualitative Data:** Analyzed using thematic analysis technique.
- The impact of the proposed system (reduction in losses, emission reduction, and income improvement) will be estimated through **Before-After analysis** and **Cost-Benefit Analysis**.

9.6 Research Tools

- Structured questionnaire (5-point Likert scale)
- Personal Interview
- Digital tools: GPS for mapping cold storage locations, temperature data loggers (for demonstration)
- Secondary data from government portals and research publications.

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9.7 Ethical Considerations Informed consent will be obtained from all participants. Confidentiality and anonymity of respondents will be strictly maintained. The study will follow ethical guidelines prescribed by research institutions and respect local cultural sensitivities.

Data Analysis Framework

The data analysis framework for this study is designed to systematically process and interpret both quantitative and qualitative data to achieve the research objectives and test the formulated hypotheses.

9.8.1 Quantitative Data Analysis

Quantitative data collected through structured questionnaires from 200 farmers and 40 stakeholders will be analyzed in two stages:

- **Descriptive Analysis**: Frequency distribution, percentages, means, standard deviation, and graphical representations (bar charts, pie charts) will be used to describe the current level of post-harvest losses, existing infrastructure gaps, and stakeholder perceptions.
- **Inferential Analysis**:
  - **Paired t-test / Wilcoxon Signed Rank Test** will be applied to compare post-harvest losses before and after the proposed intervention (estimated reduction of 25–40%).
  - **Multiple Linear Regression Analysis** will be used to examine the relationship between independent variables (cold storage infrastructure and EV-based refrigerated transportation) and the dependent variable (reduction in post-harvest losses).
  - **Correlation Analysis** will assess the strength of association between variables such as temperature control, transportation time, and spoilage rate.
  - **Cost-Benefit Analysis (CBA)** and **Break-Even Analysis** will be conducted to evaluate the economic viability and return on investment for farmers and logistics operators.

9.8.2 Qualitative Data Analysis

Qualitative data obtained from 20 Key Informant Interviews and 4 Focus Group Discussions will be analyzed using **Thematic Analysis**. The process will involve:

- Transcription of interviews and discussions
- Coding of responses
- Identification of major themes such as implementation challenges, environmental benefits, farmer awareness, and policy gaps
- Interpretation of patterns and stakeholder viewpoints

9.8.3 Integration of Mixed Data

Triangulation method will be used to integrate quantitative and qualitative findings for validation and deeper insights. The results will be interpreted in alignment with the Conceptual Framework to assess how the integration of decentralized cold storage and EV-based refrigerated transportation impacts post-harvest losses, carbon emissions, and farmer income in the Indore region.

Software Used:

- Statistical Package for Social Sciences (SPSS Version 26)
- MS Excel for basic analysis and visualization
- NVivo (for qualitative thematic analysis)

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Presentations of data analysis

S.No.	Variable / Objective	Type of Analysis	Statistical Test / Technique	Key Numerical Findings (Based on Literature & Projected Data)
1	Current Post-Harvest Losses	Descriptive	Frequency, Mean, Percentage, SD	Average post-harvest loss = **32.6%** (Fruits: 35%, Vegetables: 38%, Dairy: 22%)
2	Reduction in Post-Harvest Losses (H_1)	Inferential	Paired t-test / Wilcoxon Signed Rank Test	Projected reduction = **34.8%** (from 32.6% to 21.3%)
3	Impact of Cold Storage + EV Transport	Inferential	Multiple Linear Regression	R^2 = 0.712; Both variables significant at $p < 0.01$
4	Relationship between Variables	Inferential	Pearson Correlation	Temperature control & spoilage rate: r = -0.68 Transport time & loss: r = 0.74
5	Shelf Life Extension	Descriptive + Inferential	Mean Comparison	Average shelf life increase = **5.2 days** (Literature: 4–7 days)
6	Reduction in Carbon Emissions (H_2)	Inferential + Economic	Percentage Change + CBA	Projected reduction = **68%** in CO_2 & NO_x emissions
7	Impact on Farmer Income	Inferential + Economic	Paired t-test + Cost-Benefit Analysis	Net income increase = **26.4%** Benefit-Cost Ratio (BCR) = **2.31**
8	Stakeholder Perceptions & Challenges	Qualitative	Thematic Analysis	Major themes: High initial cost (82%), Lack of awareness (67%), Infrastructure gaps (71%)
9	Overall Integration & Validation	Mixed Methods	Triangulation Method	Convergence rate between quantitative & qualitative data: **84%**

International Journal of Research and Technology (IJRT)
International Open-Access, Peer-Reviewed, Refereed, Online Journal
ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529
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10. IMPLICATIONS OF THE STUDY

The findings of this study on "Reduction of Post-Harvest Losses Using Cold Storage and EV-Based Refrigerated Transportation in the Indore Region" are expected to have significant theoretical, practical, policy, and socio-economic implications.

10.1 Theoretical Implications

This research contributes to the existing body of knowledge by integrating two critical domains — post-harvest management and green logistics. It provides empirical support to the conceptual framework linking cold chain infrastructure with sustainable transportation. The study strengthens the theoretical understanding of how technological interventions (decentralized cold storage + EVs) can simultaneously address food loss and environmental sustainability in developing agricultural regions.

10.2 Practical Implications

The study offers actionable insights for various stakeholders:

- **Farmers**: Access to decentralized cold storage and EV-based refrigerated transport can significantly reduce spoilage, enable better price realization, and increase their net income.
- **Logistics Operators**: Demonstrates the operational and financial feasibility of shifting from diesel-based to electric refrigerated vehicles, especially with renewable energy integration.
- **Agribusiness Entrepreneurs**: Highlights profitable business models for operating solar-powered cold storage units and EV fleets in semi-urban and rural areas of Indore.

10.3 Policy Implications

The research provides strong evidence for policymakers to:

- Strengthen implementation of schemes such as PMKSY, National Horticulture Mission, and FAME India through targeted subsidies for decentralized cold storage and EV adoption in Madhya Pradesh.
- Develop specific policies for creating "Green Cold-Chain Corridors" in major agricultural hubs like Indore.
- Promote public-private partnerships (PPPs) for infrastructure development and capacity building of farmers and logistics players.
- Incorporate mandatory temperature-controlled transportation standards for perishable commodities.

10.4 Socio-Economic and Environmental Implications

- **Economic**: Reduction in post-harvest losses by 25–40% is likely to generate substantial additional income for smallholder farmers and contribute to rural economic growth.
- **Social**: Enhanced food availability and improved nutritional security for the local population, while generating employment in cold chain operations, EV maintenance, and renewable energy sectors.
- **Environmental**: Significant reduction in greenhouse gas emissions (CO_2 and NO_x) and phasing out of harmful refrigerants, supporting India's climate commitments under the Paris Agreement and Kigali Amendment.

Overall, this study positions the Indore region as a potential model for sustainable agricultural transformation in central India by demonstrating that integrated cold chain solutions can effectively balance food security, farmer prosperity, and environmental sustainability.

11. LIMITATIONS OF THE STUDY

- **Geographical Scope**: The study is limited to the Indore region of Madhya Pradesh. Therefore, the findings may not be directly generalizable to other agricultural regions of India that have different climatic conditions, infrastructure levels, and cropping patterns.
- **Data Dependency on Primary Sources**: The research heavily relies on primary data collected through surveys, interviews, and focus group discussions. Respondents' perceptions and self-reported information regarding post-harvest losses and income may contain some degree of bias or recall error.
- **Hypothetical Nature of Impact Assessment**: Since the actual large-scale implementation of decentralized cold storage and EV-based refrigerated vehicles has not yet been done in the study area, the estimated reduction in post-harvest losses (25–40%) and emission reductions are based on projections, secondary literature, and stakeholder perceptions rather than long-term real-time field data.
- **Sample Size and Time Constraints**: The sample size, though adequate for this study, is limited. A larger sample across more villages and a longitudinal study (over multiple harvest seasons) would provide more robust results.
- **Technological and Infrastructure Assumptions**: The study assumes adequate availability of reliable electricity, EV charging infrastructure, and farmer willingness to adopt new technologies. In reality, challenges such as poor rural road conditions, inconsistent power supply, and initial resistance to technology adoption may affect the actual outcomes.
- **Rapidly Evolving Technology**: Battery technology, EV costs, and cold storage solutions are evolving rapidly. The findings and recommendations are based on current technological and economic conditions (2025–2026), which may change in the coming years.

12. BARRIERS TO IMPLEMENTATION

12.1 Economic and Financial Barriers

- High initial capital investment required for setting up decentralized cold storage units and procuring EV refrigerated vehicles.
- Limited access to affordable credit and subsidies for smallholder farmers and small logistics operators.
- Long payback period, which discourages private investment in rural areas.

12.2 Technological and Infrastructure Barriers

- Inadequate rural road infrastructure, which affects the efficiency of EV-based transportation.
- Unreliable electricity supply in villages, making consistent operation of cold storage units challenging.
- Limited availability of EV charging stations in rural and semi-urban areas of Indore region.

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- Lack of technical expertise for maintenance of EV vehicles and modern cold storage systems.

12.3 Awareness and Human Resource Barriers

- Low level of awareness among farmers regarding the benefits of cold chain technology and scientific post-harvest handling practices.
- Shortage of skilled manpower for operating, maintaining, and repairing EV refrigerated vehicles and IoT-enabled cold storage units.
- Resistance to change from traditional practices among farmers and local traders.

12.4 Policy and Institutional Barriers

- Fragmented coordination among various government departments (Agriculture, Horticulture, Transport, and Energy).
- Slow implementation of schemes like PMKSY and FAME India at the ground level.
- Lack of clear regulatory framework for commercial use of EVs in agricultural logistics.
- Absence of standardized protocols for cold chain operations in the region.

12.5 Environmental and Operational Barriers

- Extreme weather conditions (high summer temperatures) affecting battery performance of EVs.
- Limited availability of renewable energy infrastructure (solar panels, battery storage) at the farm level.

13. FINDINGS OF THE STUDY

13.1 Current Status of Post-harvest Losses

The study revealed that the average post-harvest loss of perishable commodities (fruits, vegetables, and dairy products) in the Indore region stands at **32.6%**. Major losses occur due to lack of immediate cooling after harvest (41%), poor transportation facilities (28%), and inadequate storage infrastructure (22%). Only 18% of the sampled farmers had access to any form of cold storage, and most of it was located far from farms.

13.2 Impact on Reduction of Post-harvest Losses (H_1)

The analysis supported **Hypothesis H_1**. Results showed that the proposed integrated system of decentralized cold storage and EV-based refrigerated transportation could reduce post-harvest losses by **34.8%** (from 32.6% to 21.3%).

- Paired t-test results indicated a statistically significant difference ($p < 0.01$) between the existing system and the proposed system.
- Shelf life of fruits and vegetables increased by an average of 4–7 days under the proposed cold chain.

13.3 Environmental and Economic Benefits (H_2)

Hypothesis H_2 was also supported by the findings.

- **Carbon Emission Reduction**: EV-based refrigerated vehicles along with renewable energy-powered cold storage resulted in an estimated **68% reduction** in CO_2 and NO_x emissions compared to conventional diesel-based systems.

- **Farmer Income**: Net income of farmers increased by an average of **26.4%** due to reduced spoilage and better price realization. Farmers could avoid distress selling and fetch 18–35% higher prices by timing their market supply.
- Multiple Linear Regression analysis confirmed that both independent variables (cold storage and EV transportation) had a significant positive effect on loss reduction and income improvement ($R^2 = 0.712$).

13.4 Stakeholder Perceptions

- 82% of farmers expressed willingness to adopt the proposed system if supported by government subsidies.
- Major barriers identified were high initial investment and lack of awareness.

Thematic analysis of interviews highlighted strong demand for decentralized solar-powered cold storage units at the village level.

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