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Assessment of Energy-Efficient and Clean Energy Technology in the Cold Chain Sector

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Highlights

- The cold-chain infrastructure in India is anticipated to expand dramatically over the next few years, increasing the cooling demand and corresponding energy consumption.
- It uses cutting-edge technology to keep temperature regulation at a precise level. Assessing current technologies and encouraging efficient technology is crucial to lowering energy demand.
- The findings from the study will be helpful to government agencies involved in developing the cold-chain sector. Technology providers, researchers, and cold-chain owners will benefit by understanding the technologies present in the sector.

Abstract

There is a growing need for the cold-chain sector due to the demand for fresh and frozen products. With the increase in growth of the cold chain sector, the related energy consumption will increase, and to address the issue, emphasis needs to be given to energy-efficient and clean energy technologies. By utilizing these methods, expenses can be decreased, increasing the cold-chain industry's profitability and sustainability. The authors aim to identify the available technologies and focus on adopting efficient technologies to improve the cold chain's efficiency, reduce costs, and ensure product quality and safety in the cold-chain sector by reviewing relevant literature, stakeholder consultation, and case studies.

Keywords: Cold chain, Horticulture, Food Loss, Cooling Technologies

Introduction

India has witnessed an increase in horticulture production over the last few years. The production of horticulture crops in 2021-22 has been pegged at a record 341.63 million tonnes, 2.9 percent higher than the final estimate for 2020-21. The production of vegetables alone is estimated to be 204.61 million tonnes, while fruit production is estimated to be 107.10 million tonnes [1]. Horticulture contributes 30.4 percent of agriculture's gross domestic product (GDP), using only 13.1 percent of the gross cropped area [2]. Over the years, total horticulture production in the country has surpassed the total food grains production, achieving a higher production record every year. Despite all these achievements, the horticulture sector faces substantial post-harvest losses, a lack of storage infrastructure, price seasonality, and market volatility.

Furthermore, small-holder farmers, who account for 86% of all farmers in India and own half of the arable land, still struggle with low-income levels and huge food losses throughout the supply chain [3]. These farmers fail to benefit from post-harvest management facilities because of the limited access to cold-chain logistics and other financial barriers, further shortening the lifespan of their horticulture produce. Subsequently, the reduced lifespan causes a significant loss in their production value and livelihoods. Due to this, a considerable part of the population continues to face challenges related to food insecurity and malnutrition. A comparative study by the Centre Institute of Post-Harvest Engineering and Technology (CIPHET, 2015) reported that about 16 percent of fruits and vegetables are lost post-harvest [4]. Thus, urgent steps are needed to integrate and revamp the horticulture production and value chain system, promoting healthier and more nutritious foods and improving farmers' income.

To address these issues, the Government of India recognizes that cold-chain infrastructure is thus one of the crucial factors in the post-harvest process because it is where the commodity can sustain most of its lifetime. However, storage infrastructure is particularly pertinent for India because of inferior coordination between supply and demand, seasonality, and the perishable nature of horticulture crops. The cold-chain infrastructure mainly consists of three essential pillars: a static infrastructure for aggregating and storing the produce, reefer transport for connecting the link between the post-production and pre-market stage, and market channels for the transaction of the crop. The integrated development of the cold chain facilities in the country needs to be more robust, with major essential components of the cold chain needing to be adequately developed.

The development of cold chains is crucial for preserving product quality, preventing spoilage, and ensuring the safety of perishable items. As per ICAP, around 500 packhouses are there in India at present consuming 0.02 TWh electricity; the number is likely to grow to 55,000 by 2027-28 and to 1,25,000 by 2037-38, attributing to the energy consumption of 2.4 TWh and 5.2 TWh, respectively. The growth of reefer vehicles is related to an increase in the packhouse, and their estimated numbers are 1,35,000 units in the next decade and 4,00,000 units in the subsequent decades from the present 15,000 units with related energy consumption of 4000 TJ at baseline and 40,000 TJ by 2027-28 and 1,25,000 TJ by 2037-38 [5]. Energy consumption in the cold chain primarily stems from packhouse refrigeration systems, including refrigerated trucks, warehouses, and display units. The growth in the development of infrastructure is necessary. However, there are challenges such as high energy cost, operational efficiency, high cost of technology, and unskilled workforce. Addressing these challenges will be essential for the cold chain sector to realize the benefits of scaling up the technology and meet the growing demand for temperature-sensitive products.

Energy consumption in the cold chain is involved within each component of the cold chain in terms of fuel or electricity. Due to the insufficiency of data, the author has focused primarily on the packhouse and shared a few details on reefer trucks. The authors aim to identify the available technology used in sorting, grading, packing area, pre-cooling chamber, staging room, and reefer truck through an evaluation framework model which would improve efficiency, reduce costs, and ensure product quality and safety in the cold chain sector by reviewing relevant literature, stakeholder consultation, and case studies. Consequently, the research paper also highlights some of the plug-in technologies that can be used to make the cold chain sector more robust.

The model will focus on technologies available in the following categories:

- Cooling Technology
- Refrigerant
- Insulation
- Plug-In Solution
- Energy Sourcing

Each of these categories will be evaluated based on appropriate parameters.

Methodology

The research paper is intended to be a comprehensive study that builds upon a thorough understanding of the best available industry knowledge. The document has tried to plug some information gaps through a multi-source methodology adopted by the author, which triangulates inputs from existing government databases, market intelligence reports, secondary research from other reliable sources, and interviews with subject matter experts. The data was obtained through consultations with refrigeration system manufacturers such as Danfoss, Carrier, Voltas, Blue Star, etc., Cold room manufacturers such as Inficold, Pluss Advance Technologies, New Leaf Dynamics, etc., refrigeration institutions like RAMA, ISHRAE, and service provider such as Standard Refrigeration, Ice Make Refrigeration, etc.

The technology used in each component of the cold chain was identified and compared based on relevant parameters. Significant inputs are sourced from consultations with various technology providers, and efforts were made to consolidate data obtained and assess each technology.

Cold Chain and its components

According to the NCCD definition, a cold chain is a temperature-controlled environment logistic chain, ensuring uninterrupted handling of products from source to user, consisting of storage and distribution-related activities in which the inventory is maintained within predetermined ambient parameters. The cold chain essentially serves two primary purposes, namely maintaining a product’s quality and prolonging a product’s life without changing the core features of the product handled.

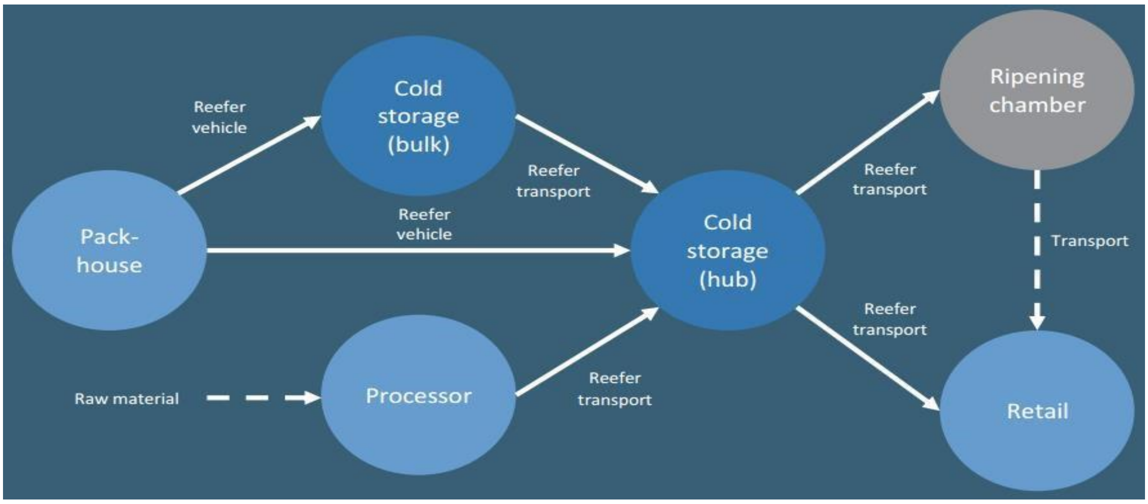

Figure 1: Flow of process in a cold chain

In the case of fresh fruits and vegetables, the cold chain infrastructure must offer a more precisely controlled environment regarding humidity and microbial conditions, oxygen level, monitoring and control of degenerative gases, and segregation to avoid tainting between living tissue and maintaining a precise temperature. According to ICAP 2019, the flow of products in a typical cold chain is shown in Figure 1. Data shows that most food losses related to fruits and vegetables are between the farm gate and post-harvest handling. To reduce these losses, a packhouse facility is an appropriate solution for correctly handling, pre-cooling, and packaging the produce. In the product's supply chain, the reefer or refrigerated trucks are crucial in transporting the produce at a required temperature.

Integrated pack house

This component refers to a modern integrated pack-house with facilities for a conveyor belt system for sorting and grading, washing, drying, and weighing. A modern integrated pack-house unit enables small lot sourcing of horticulture produce and should be built close to the farming area. The "Integrated Pack-house" component includes a covered receiving area, an enclosed covered sorting and grading area, sorting and grading conveyors, washing/drying equipment, a packaging area, an electricity generator, etc. Additionally, washing, drying, and weighing equipment can be installed to read the product for packaging.

Pre-cooling unit

The component Pre-Cooling Unit is a specialized cooling room that rapidly removes field heat from fresh produce after harvest, preparing the cargo for subsequent shipping. The temperature differential between the harvested crop's temperature and the produce's ideal storage temperature is called the "field heat." Generally, the temperature should be lowered until 88% of the current temperature difference from its ideal storage temperature [6]. The humidity depends on the produce storage requirements, which may vary from 80% - 95% RH in the case of fresh fruits and vegetables. The "Pre-cooling unit" component includes an insulated room, pre-cooler unit, evaporating and condensing unit, electronic controller, electricity generator, etc. The refrigeration system uses the majority of the energy in the pre-cooling room; therefore, it is crucial to evaluate the cooling technology applied in the pre-cooling unit.

Cooling technology for pre-cooling unit

Field heat must be removed from freshly picked perishable vegetables to slow metabolism and deterioration before storage. The amount of produce that needs to be chilled, the air temperature, airflow rate, relative humidity, the packing configuration and stacking arrangement of the produce, the energy efficiency of the method, the availability of a skilled operator, and the economic viability of the pre-cooling all play a role in the decision of which pre-cooling technique to use for fruits and vegetables. Some of the significant pre-cooling methods are compared based on specific parameters in Table 2.

Table 1: Comparison of pre-cooling methods

Technology	Refrigerated Room cooling	Forced air cooling	Hydro cooling	Ice cooling	Evaporative cooling
Typical cooling time (h)	20 to 100	1 to 10	0.1 to 10	0.1 to 0.3	0.3 to 2
Product moisture loss (%)	0.1 to 2	0.1 to 2	0 to 0.5	No data	No data
Water contact with the product	No	No	Yes	Yes, unless bagged	Yes
Potential decay	Low	Low	High	Low	High
Capital cost	Low	Low	Low	High	Medium

Energy efficiency	Low	Low	High	Low	Medium
Water-resistant packaging needed	No	No	Yes	Yes	Yes
Portable	No	Sometimes	Rarely done	Common	Common
Feasibility of in-line cooling	No	Rarely done	Yes	Rarely done	No

Note- Source: ASHRAE Handbook 2021

Refrigerated room cooling techniques are typically used in traditional cold storage; however, this technology demands more energy due to comparatively higher cooling time. Evaporative cooling technology is humidity-dependent technology. The cooling effect diminishes in areas with high humidity, making evaporative cooling less effective. However, it works best in dry climates with a low humidity range. In comparison, hydrocooling is an efficient technology for pre-cooling with low capital cost. The system's potential decay is much higher than other technologies. Forced air cooling is primarily used technology in pre-cooling rooms as it uses a rapid cooling technique, although it demands higher energy for the cooling process.

A few parameters, such as capital cost, efficiency, and potential decay of these technologies, are defined as low, medium, and high due to data insufficiency. The operational cost depends on various factors such as system efficiency, ambient temperature, usage patterns, type of produce stored, etc.

Staging cold-room

This component is an insulated and refrigerated chamber, a necessary combination for the pre-cooling unit. It serves as a temporary storage while allowing the pre-cooler to be utilized for the next batch load of incoming produce. The "Cold room (staging)" component includes an insulated room, associated refrigeration equipment, staging area, etc.

Cooling technologies for staging

Two principal types of technologies are found in the cold chain sector: (1) Vapour Compression Refrigeration (VCR) and (2) Vapor Absorption Machine (VAM). VCR technology makes up most cooling systems used in staging areas or for bulk storage.

VCR uses mechanical energy as the driving force for refrigeration to remove heat through the evaporation of refrigerant at low pressure and condensation of the refrigerant at high pressure. The compression refrigeration cycle consists of circulating a liquid refrigerant through four stages of a closed system. As the refrigerant circulates through the system, it is alternately compressed and expanded, changing its state from a liquid to a vapor. As the refrigerant changes state, heat is absorbed and expelled by the system, lowering the temperature of the conditioned space.

VAM belongs to the class of vapor cycles similar to the Vapour compression refrigeration system. However, unlike VCR, the required input to the absorption system is in the form of heat. Hence, these systems are also called heat-operated or thermal energy-driven systems. The method of creating the pressure difference and circulating the refrigerant is the primary difference between the two cycles. The performance of cold storage only depends on the temperature. The lower the temperature inside the cold chamber, the greater the performance. Table 3 compares both cooling technologies based on parameters such as capacity range, CAPEX, OPEX, COP, and skill required for operation.

Table 2: Comparison of cooling technologies for staging

Technology	**VAM**		**VCR**	
	Min	Max	Min	Max
Commercially available Range (Temperature of refrigeration-TR)	50	1,550	1	2,800
CAPEX (INR Lakhs)	60-70 (25 TR)		65 (50TR)	
OPEX (INR Lakhs/year)	5-15 (approx.)		15-20 (approx.)	
Coefficient of performance	1.45 - 1.50		2 - 3.60	
Maintenance/skill required	High		Low	

Note- Source: The data mentioned in the table is for direct-fired VAM. The COP of the system may vary depending on various factors, such as load condition, ambient temperature, etc.

VCR systems are generally more energy efficient than VAM when used for small to medium-scale cooling applications. VAM systems tend to have lower energy efficiency; however, they have advantages in specific niche applications where waste heat or low-grade heat sources are readily available, making them more cost-effective.

Insulation

Insulation minimizes heat transfer and protects the stored product from external temperature fluctuation. It is typically achieved through specialized materials with high thermal resistance, such as foam panels or polyurethane foam. These materials are placed in the refrigerated storage areas' walls, floor, ceiling, reefer truck, and cold storage warehouse. Insulation plays a significant role in reducing overall energy consumption by decreasing the load on the refrigeration system. Insulating the pre-cooling and staging room with optimal thermal performance could save around 3-5% of the overall refrigeration (cooling) energy consumption [7].

Table 3: Comparison of insulation materials used in cold storage

Sr. No.	Panel	Thermal conductivity (W/m. K)	Fire resistance	Panel density (kg/m^3)	Water absorption rate	Cost (INR/m^2)	Lifespan (years)
1	Polyurethane foam (PU or PUF)	0.022-0.028	B2, B1	35 - 45	2.5% - 3%	1,300	25
2	Extruded polystyrene foam pane (XPS)	0.025-0.040	A	22-26	0.03%	840	Building lifetime
3	Expanded polystyrene foam pane (EPS)	0.030-0.040	B1	10-26	2% -4%	600	35-50
4	Mineral wool	0.020-0.040	A	32-100	0.3%	500	Building lifetime
5	Glass wool	0.023-0.040	A	16-48	<2%	450	Building lifetime

Insulation panels should have five essential characteristics: (i) excellent thermal insulation, (ii) perfect sealing, (iii) strong anti-compression, (iv) anti-bending, and (v) vapor barrier (anti-condensation insulation). Prefabricated panels, an emerging standard material, can serve as permanent walls and insulation for roofs. These panels act as vapor barriers and resist moisture flow from both sides.

Additional energy efficiency measures

Energy efficiency improvement in the packhouse can also be implemented through intervention in building design, equipment and system design, and packhouse operation and maintenance. The table below presents the energy efficiency measures that can be used for improving efficiency along with its energy-saving potential:

Table 4: Energy efficiency measures for packhouse

Energy efficiency measures	Energy saving potential	Remarks
Natural lighting, proper orientation, and Shading	Indicative energy saving potential can be 1-2% of total energy consumed. The reduction in cooling demand is around 1%.	The orientation of the building should be such that the longer façade faces North-South and the short façade faces East-West.
Wall and Roof Insulation	The energy-saving potential is 1-2% of the total energy consumed in a packhouse	Insulation will reduce heat gain inside the building by reducing the conductive heat transfer from the wall and roof.
Cool roof treatment	The energy saving potential is estimated at around 0.5-1% of total energy consumed.	Cool roof treatment using low-cost interventions like highly reflective china-mosaic tiles.
Air-tight doors for pre-cooling and cold rooms	The saving potential in overall energy consumed in cooling is around 2%.	Use of gaskets, hinges, and latches made of industrial-grade stainless steel materials.
Fast roll-up doors to prevent hot/moist air infiltration	The saving potential in overall energy consumed in cooling is estimated to be around 6-8%.	
Low-energy evaporative cooling system for temperature control in the packing hall	The energy-saving potential of evaporative cooling over an airconditioned space can be up to 40-50%	Suitable for the hot & dry and composite climatic conditions.
Energy-efficient refrigeration system configuration for pre-cooling and staging room	Semi-hermetic reciprocating or scroll compressors in a rack system can potentially reduce energy consumption by 15-20%. A water-cooled/Evaporative condenser can potentially reduce energy consumption by 20% over the air-cooled system.	The compressor rack system works more efficiently compared to the independent one-to-one compressor.
Energy Management System	The accurate setting of plant operation parameters, including the right suction pressure and discharge pressure, can potentially improve the overall system efficiency by 8-10%	PLC-based refrigeration plant operation will enable real-time monitoring and help optimize the cooling demand

Plug-in solution / Micro cold room

Technology development has accelerated in India in recent years due to a rise in demand for storing fruits and vegetables at the farm gate. Governments realize the necessity of farm-gate storage of fresh produce to increase their shelf life; hence, the plug-in solution/micro cold room is being promoted. Some start-ups have arisen with their creative approaches to preserving produce at the farm gate. These products represent some intriguing market advancements. Since most of these solutions are off-grid capable, they work best when implemented in regions with highly erratic grid electricity supply.

Table 5: Comparison of plug-in solutions

Parameter	Ecozen	Inficold	CoolCrop	Promethean Power System	Oorja	New Leaf Dynamics
Key Products	Eco frost – solar cold storage room	Solar cold room	Cold storage solutions	Cold storage solutions	Solar powered refrigeration	Green chill
On/off Grid	On-grid	On-grid	On-grid	On-grid	On-grid	Biomass
Storage capacity range	5-10 MT	5-10 MT	2-10 MT	0.50-2 MT	5-10 MT	10-20 MT
Temperature range	4-10 °C	4-20 °C	0-18 °C	2-4 °C	4-10 °C	-2-25 °C
Electrical backup	NA	NA	NA	Yes	NA	NA
Thermal backup	PCM plates	Water	PCM lined Walls	PCM	PCM plates	NA
Digital platform	Predictive diagnostics- AI & Data Science	Cloud-based management & Inventory management	Crop Management Platform, Market Analytics	App-based management for the system Performance	Predictive diagnostics- AI & Data Science	NA
Financial model	Lease model, Sales model	Sales model	Lease model, Sales model, Cooling as a Service model	Lease model, Sales model	Cooling as a service – uses Eco Frost model	Sales model
CAPEX	7.50-10 lakhs/unit	11-12 lakhs/unit	4.50-5 lakhs/unit	8-10 lakhs/unit	Tariff: INR 0.30 per kg per day Membership fee: INR 1,000	15-20 lakhs/unit

Note: The data is obtained through consultation and companies' websites

Energy Sourcing

In the cold chain, which involves storing and transporting temperature-sensitive goods, energy sourcing plays a crucial role in maintaining proper temperature conditions and ensuring product integrity. The majority of the packhouses in India source energy from the grid and use diesel generators as a backup system. However, the owners of packhouses face significant difficulties due to the high energy cost through the grid and its dependability in remote places. As a result, it is essential to explore renewable energy sourcing methods as a substitute energy source for the packhouse. The grid may serve as a balancing source when there is either an excess or a lack of onsite renewable energy generation.

Table 6 provides a high-level distributed renewable energy generation technology assessment. Solar PV is commercially and financially the most attractive distributed energy generation technology today. Biogas and biomass technologies with a competitive Levelized Cost of Electricity (LCOE) and unintermittent generation potential are attractive options, provided that an adequate type and quantity of feedstock at an affordable rate is available.

Table 6: Technology assessment of renewable energy sourcing

Technology	Solar PV	Biogas	Biomass	Solar Thermal1
LCOE range	INR 4.15-5.05/kWh	INR 7.13-14.25/kWh	INR 4.5-21.75/kWh	INR 13.65-32.25/kWh
Commercial availability	1 kWp and onwards	3 kW and onwards	10 kW – and onwards	6 kW and onwards
Technology readiness (TRA)	Fully Commercialized	Fully Commercialized	Fully Commercialized	Partially Commercialized
Resource	Solar Irradiance (No minimum value)	Feedstock with moisture	Dry feedstock	Solar Irradiance (Minimum 350 W/m^2)
Area required	10 m^2 for 1 kWp	560 m^2 for 40 kW	NA	16 m^2 aperture area & 35 m^2 shadow free are for 6 kW
Intermittency	Hourly	NA	NA	Hourly

Conclusion

The cold-chain sector plays a vital role in preserving the quality and safety of perishable goods, such as food and pharmaceuticals. However, it is also associated with significant energy consumption and high operating costs. To address these challenges, the report identifies and evaluates various efficient and innovative technologies that can be integrated into cold-chain operations to reduce energy consumption and minimize environmental impact. These include efficient cooling solutions, advanced insulation materials, building design and orientation, energy-sourcing options, etc.

Primary and secondary research carried out under this study indicates that there is untapped potential for energy performance improvement in the cold-chain sector. Cross-cutting technologies such as solar-based cold rooms are invented to reduce grid reliability in remote areas, making farm gate storage accessible to marginal and small farmers. A Low-energy evaporative cooling system can be deployed for temperature control in the packing hall. It can effectively provide favorable post-harvest environmental conditions required for fruits and vegetables. Energy efficiency measures include proper orientation and shading, insulating roof and wall, cool roof treatment, air-tight doors, etc. play a vital role in energy savings. The research paper focuses mostly on farm gate storage, which includes the micro cold room and packhouse; reefer trucks and large cold storage facilities are not included. The upcoming study will address the broad elements of the cold chain.

The report underscores the urgent need for efficient and sustainable solutions in the cold-chain industry. By leveraging energy-efficient technologies and innovative approaches, stakeholders can reduce operating costs, minimize environmental impact, and improve the overall efficiency of cold-chain operations.

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