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An Evaluation Framework for Deploying Energy-efficient, Climate-friendly Cold Rooms for Agriculture Cold-Chain in India

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Highlights

- Evaluation framework for energy-efficient agriculture cold rooms.
- Enabling sustainable cold-chain for agri-business.
- Inclusion of energy efficiency in government subsidies.

Abstract

Post-harvest losses in India are estimated to be 6-15%, with an annual value of about Rs 1 lakh crore. Produce loss impacts farmers' incomes. Further, every wasted ton of fruit and vegetable decomposes into ~1.5 tons of greenhouse gases. Effective post-harvest protocols and integrated cold-chain infrastructure are essential to reduce post-harvest losses. However, there is a 97% gap in integrated pack-houses. Integrating sustainable technologies in the upcoming cold-chain infrastructure could contribute to a sustainable agri value chain, potentially reducing energy and refrigerant demand compared to business-as-usual scenarios. Currently, there are insufficient guidelines for assessing energy-efficient, climate-friendly technologies for cold-chain. This paper presents an evaluation framework to assess energy efficiency, energy supply, and refrigerants in cold-chain product offerings. The framework was used to evaluate cold room solutions from nine vendors. The framework can be integrated into government schemes for cold-chain and enable agri-businesses to assess and deploy energy-efficient, climate-friendly cold rooms.

Keywords: cold-chain, energy-efficient, pre-cooling, staging cold room

Introduction

Post-harvest losses in India are estimated to be 6% in cereals, 8% in pulses, 10% in oilseeds, and 15% in fruits and vegetables, with an annual value of about Rs 1 lakh crore [1]. Produce loss impacts farmers' incomes and livelihoods. Further, every wasted ton of fruit and vegetable decomposes into ~1.5 tons of greenhouse gases (GHG) [2]. Effective post-harvest protocols and integrated cold-chain infrastructure are essential to reduce post-harvest losses and to enable value-addition for produce. Per the India Cooling Action Plan (ICAP) 2019, there is a 97% gap in integrated pack-houses with processes for sorting, grading, washing, packing, pre-cooling, and staging cold rooms [3]. Integrating energy-efficient and climate-friendly technologies in the upcoming cold-chain infrastructure could ensure a sustainable built trajectory, potentially reducing energy and refrigerant demand compared to business-as-usual scenarios. While the central and state governments have schemes to support the development of cold-chain, there are no published standards for the energy performance of cold-chain equipment and insufficient guidelines for assessing and deploying energy-efficient, climate-friendly technologies.

The Bureau of Energy Efficiency's (BEE) Standards and Labeling (S&L) program was instrumental in increasing consumer awareness and acceptance of energy-efficient appliances, leading to increased penetration of energy-efficient appliances in the market. Likewise, demonstrating energy-efficient, climate-friendly cold-chain technology, supported with technology evaluation guidelines and standards, is critical to building the credibility of energy-efficient, climate-friendly cold-chain solutions. Further, technology evaluation guidelines and standards will advance consumer awareness and acceptance of energy-efficient, climate-friendly cold-chain solutions, benefiting farmers and agribusinesses while helping to meet India's climate action goals.

The objective of this project is to demonstrate sustainable cold chain solutions to improve farmers' incomes and reduce post-harvest losses. The authors surveyed forty-eight Farmer Producer Companies (FPCs) and completed field visits to nine FPCs to identify use cases where cold-chain solutions would benefit farmers in reducing losses, preserving produce quality, and increasing produce value. The team identified four use cases for a technology demonstration of energy-efficient, climate-friendly cold rooms, of which one use case was selected. The team met with manufacturers of cold-chain equipment to learn about their products and consulted agriculture experts on the requirements for cold-chain in post-harvest management. The methods for evaluating cold-chain product offerings from vendors, selecting an optimal solution for pre-cooling and staging cold rooms, and the way forward are described in the following sections of the paper.

Methodology

In accordance with standard government procurement procedures, the selection process for sustainable cold-chain solutions can be divided into two primary stages: the Request for Proposal (RfP) preparation stage and the proposal evaluation stage.

The RfP preparation stage further comprises four steps:

1. Defining the necessary cold-chain solutions, such as pre-cooling and staging cold rooms, and the details of produce throughput.
2. Establishing weightage for technical and financial evaluation scores.
3. Setting the technical and financial evaluation criteria, as detailed in the Evaluation Framework section.
4. Defining additional terms and conditions, like payment terms and other requirements, which may include annual reports, audited balance sheets, or turnover statements.

The proposal evaluation stage also involves four steps:

1. Allocating weightage for technical and financial evaluation within the necessary specifications (criteria).
2. Defining the scoring criteria for the technical and financial evaluations.
3. Scoring based on the data provided in the techno-commercial proposals submitted by interested vendors.
4. Conducting reference checks on shortlisted vendors to obtain feedback from their existing customers.

The RfP, which could be dispatched to chosen vendors or opened for bidding, encompasses the items specified in the Evaluation Framework. Certain technical or financial evaluation criteria may be made obligatory, potentially disqualifying vendors for non-compliance. The final vendor is selected based on the combined technical and financial evaluation score and satisfactory reference checks. This evaluation framework provides a systematic method for choosing sustainable cold-chain solutions that support rural livelihoods and mitigate food losses.

Evaluation Framework

The framework for evaluating a cold room encompasses both technical and financial aspects. The suggested weightages for the technical and financial criteria in the cold room evaluation framework have been carefully determined to ensure a balanced assessment of the project's overall performance and sustainability. In government tenders and other similar evaluations, it is expected to allocate a higher weightage to technical aspects, as they directly impact the cold room's efficiency, reliability, and functionality. The weightage for technical and financial evaluation could be 70:30, adhering to the standard practice observed in government tenders. With a 70% weightage on technical criteria, the focus remains on the quality of design and implementation, which are crucial for achieving optimal performance and meeting the desired objectives.

In distributing the evaluation weightages within the technical criteria, the framework aims to comprehensively assess the cold room's design and functionality, aligning with the overall 70% technical weightage. Each aspect's suggested weightage aims to emphasize its significance: 20% dedicated to refrigeration system design to ensure energy efficiency and sustainability in the active cooling system, 12% for design intent to guarantee alignment with project goals, 10% for envelope design to maintain thermal integrity, and 7% each for renewable energy integration, monitoring and control, supply and installation, and operations & maintenance, all collectively contributing to the cold room's efficiency and longevity. This balanced distribution reflects the comprehensive evaluation needed to attain a successful cold room project.

In terms of financial criteria, the framework examines the upfront capital expenditures (CAPEX) (15% weightage) and operational expenditures (OPEX). The OPEX includes energy costs, i.e., either electricity or other fuels such as biomass (5% weightage) and O&M expenditures (10% weightage) associated with the cold room. The rationale behind the allocation of evaluation weightages for the financial criteria underscores the economic viability and sustainable operation of the cold room project.

While the two financial criteria are self-explanatory, below is a comprehensive description of the seven technical criteria and their respective sub-criteria, along with suggested evaluation weights:

1. Design Intent (12% weightage)

Produce incoming temperature (2% weightage): This sub-criterion refers to the temperature at which the produce enters the cold room or pre-cooling room. It depends on the source of procurement of the produce, i.e., either from the field or collection centre, or wholesale market. The handling and transportation practices also affect the incoming temperature of the produce. This information is used in the heat load calculation analysis for refrigeration system design and sizing.

Design temperature (produce outgoing) (4% weightage): This sub-criterion refers to the desired temperature condition for the produce to be maintained in the cold room or cooled down to in the pre-cooling room. The temperature range depends on the type of produce being stored and is specified in technical standards like NHB-CS-Type 02-2010 [4], which further refers WFLO Manual [5]. Maintaining the recommended temperature range helps to extend the storage life of the produce.

Design relative humidity (produce outgoing) (4% weightage): This sub-criterion refers to the desired relative humidity (RH) condition for the produce to be maintained or achieved in the cold room or pre-cooling room. The RH level required depends on the specific storage needs of the produce being stored and is specified in the NHB standard [4]. Maintaining the recommended RH level helps to prevent moisture loss or spoilage of the produce.

Lighting condition (2% weightage): This sub-criterion refers to the need to maintain dark storage conditions for perishable fruits and vegetables that are sensitive to light. Exposure to light can affect the visual appeal of the produce and make it less desirable to consumers. NHB standard [4] recommends dark storage conditions for such produce.

2. Envelope Design (10% weightage)

Layout of Pre-cooling and Staging Cold Rooms (1% weightage): This sub-criterion requires detailed drawings that show the plan, elevation, and sectional views of the pre-cooling and staging cold rooms with measurements. These drawings are important for designing the overall infrastructure and ensuring alignment with other facilities, such as distribution centres.

Internal Stacking Layout of Crates and Pallets (1% weightage): The internal stacking layout of crates and pallets inside the cold room or pack-house must be shown in plan and sectional views, along with measurements. This sub-criterion ensures that the cold room or pack-house dimensions are optimised for the handling capacity of the produce and that there is sufficient space for air movement around the crates to ensure effective and uniform cooling. As per NHB standard [4], crates, boxes, and bins should be well-ventilated, and the pallets should be stacked with four to six-inch-wide air channels to ensure adequate cooling. Improper stacking can cause poor air distribution and a decreased cooling rate leading to uneven cooling of all the stored produce. To optimise storage, multi-commodity cold storage chambers/facilities should use polyvinyl chloride (PVC) crates, bins, and ventilated cardboard boxes stacked in pallet frames, while jute/nylon net bags in pallet frames can be used for commodities not requiring rapid cooling.

Internal Floor Area (ft^2) (1% weightage): This sub-criterion involves the calculation of the interior floor area of the cold room from the measurements on the layout.

Internal Volume per MT (ft^3/MT) (1% weightage): The internal volume of the cold room should be calculated from the measurements on the layout. NCCD guidelines [6] state that 1 MT (metric tonne) of storage capacity requires 3.4 m^3 (cubic meter) or 120 ft3 (cubic feet) of temperature-controlled storage space and 11 m^3 (cubic meter) per 1 MT of storage capacity for ripening chambers. However, the internal volume required per MT of produce in the pre-cooling room is not specified in the referred NCCD guidelines.

Type, Thickness, and Density of Thermal Insulation for Walls, Roof, and Floor (2% weightage): This sub-criterion specifies the type, thickness, and density of thermal insulation materials used for walls, roof, and floor of the cold room. The insulation materials must have low thermal conductivity to reduce the amount of heat that can pass through the walls, ceiling, and floor of the cold room. The selection of insulation material is based on the desired temperature range and given ambient conditions. The NHB standard [4] outlines the minimum insulation thickness for different insulation materials to achieve the recommended U-values for cold storage, maintaining temperatures between -4 and +2°C.

Blowing agent used in PUF panel manufacturing (1% weightage): This sub-criterion focuses on the blowing agents used to manufacture PUF panels. It is important to ensure that the blowing agents used do not have high ozone-depleting potential (ODP) or global warming potential (GWP). The criteria for selecting appropriate blowing agents must be met to ensure that the manufacturing process is environmentally friendly.

Vapour barrier in wall and roof panels (1% weightage): This sub-criterion pertains to the importance of vapour barriers in wall and roof panels made of polyurethane foam (PUF). The PUF panels are sandwiched between pre-painted galvanized iron (PPGI) sheets that act as a moisture barrier. The appropriate thickness and level of galvanization of the PPGI sheets must be selected to provide the necessary moisture barrier and structural support to the PUF panels. The vapour barrier must be designed to prevent the ingress of moisture from both sides to avoid derating the thermal performance of the PUF panels over their life.

Air-tight doors (with stainless steel handles and hinges) and pressure relief valves (1% weightage): This sub-criterion emphasizes the importance of air-tight doors in cold rooms or pre-cooling rooms. Air-tight doors are critical to maintaining the thermal integrity of the cold room and preventing any leakage that may increase heat loads on the refrigeration system. Stainless steel (SS) handles and hinges are recommended for the durability of the door fittings. Pressure relief valves are also critical safety features that prevent damage to the door and injury to individuals in case of excess pressure. Proper construction and installation of the door frame, gasket, and hinges must be ensured to maintain a tight seal when the door is not in use.

Strip curtain or air curtain (1% weightage): This sub-criterion deals with energy-efficient barriers used in cold rooms or pre-cooling rooms to reduce air transfer and consequently minimize heat transfer and energy loss and maintain a consistent temperature. Two types of energy-efficient barriers are commonly used: strip curtains and air curtains. Strip curtains are made of PVC material and hang from a header mounted above the doorway. The strips overlap and create a barrier that allows people and equipment to move through while minimising the transfer of air. On the other hand, air curtains use a high-velocity stream of air to create a barrier between the inside and outside of the cold room. They are mounted above the doorway and blow a stream of air downward, preventing warm air from entering the cold room while allowing people and equipment to move through the doorway. Both strip curtains and air curtains effectively maintain temperature control, reduce energy costs, and protect against insects, dust, and other contaminants. The NHB standard [4] recommends strip curtains for cold rooms and air curtains for external outlets/inlets.

3. Refrigeration System Design (20% weightage)

Heat load calculations (3% weightage): This sub-criterion involves calculating the amount of heat that must be removed from the cold room or pre-cooling room to maintain the desired temperature and humidity levels. The heat load calculation considers ambient conditions, room size, insulation properties, produce load, door usage, and lighting. This calculation helps determine the appropriate refrigeration system, including the capacity and size of the outdoor refrigeration unit and the type and quantity of indoor evaporators. NHB standard [4] suggests using ASHRAE handbooks [7], [8] for heat load calculations and 0.4% annual design conditions of the location for ambient conditions to size the refrigeration system appropriately. Refrigeration capacities must be calculated at different operating conditions and should include arrangements for capacity control.

Refrigeration system details (2% weightage): This sub-criterion deals with selecting the type and number of compressors, condensers, and evaporators based on the application. For cold rooms, ceiling-suspended or wall-mounted evaporators are typically used, while for pre-cooling rooms, a floor-mounted evaporator unit with a recirculating water sprinkler is generally recommended. According to the NHB standard [4], vapour compression systems are commonly used for cold storage, but absorption systems can also be utilized where heat is readily available. The air handling units for pre-cooling should be specially designed for faster cooling with high RH.

Humidification system (1% weightage): This sub-criterion involves maintaining a specific humidity level to preserve the freshness and quality of perishable produce in pre-cooling or staging cold rooms. Humidification systems prevent moisture loss and ensure that the produce remains fresh. The NHB standard [4] recommends maintaining a low delta temperature in the cooling coil to achieve higher humidity levels of 85-90%, but during loading periods or if the humidity level exceeds 90%, a separate humidification system is strongly recommended.

Cooling capacity (1% weightage): This sub-criterion on the capacity of the refrigeration system for the cold room or pre-cooling room is determined by the heat load calculations.

Refrigeration system efficiency at different operating conditions (3% weightage): This sub-criterion involves specifying the coefficient of performance (COP) of the refrigeration system for different operating conditions, not just the design conditions. The efficiency of a vapour compression refrigeration system is heavily influenced by the type and efficiency of the compressor and the size and design of heat exchangers used. The COP is the ratio of cooling capacity and power input and should be specified for different combinations of evaporating and condensing temperatures.

Variable speed operation principle (2% weightage): This sub-criterion emphasizes the importance of variable frequency drives (VFDs) in efficiently operating refrigeration systems, especially under varying load conditions and ambient temperatures. By regulating the speed of compressors and fans, VFDs can match the actual cooling requirements and prevent damage from sudden power surges, leading to significant energy savings and noise reduction. The NHB standard [4] recommends using VFDs on fans to realize energy savings, but it does not mention their application on the refrigeration system compressor.

Refrigerant type (4% weightage): This sub-criterion highlights the impact of refrigerant choice on the environmental performance of refrigeration systems. The recommended approach is selecting refrigerants with zero ozone depletion potential (ODP), low global warming potential (GWP), and good heat transfer characteristics. While natural refrigerants such as ammonia have zero ODP and GWP, their safe use must comply with national and international safety regulations due to toxicity concerns. The NHB standard [4] recommends ammonia as the best refrigerant in terms of environmental and energy performance. Still, it also provides guidance for using alternatives such as R-134a and R-404a if there are restrictions on using ammonia at certain locations. However, the standard does not offer specific guidance on selecting refrigerants based on their overall energy and environmental performance.

Air circulation (1% weightage): This sub-criterion pertains to adequate air circulation in a cold room or pre-cooling room. Proper air circulation helps maintain uniform temperature and humidity levels throughout the room, prevents the formation of hot spots, and distributes cold air evenly. Strategically placed evaporator units that circulate cold air throughout the room can achieve this. The velocity and direction of the airflow can be adjusted to meet the specific requirements of the room and the horticultural produce being stored. This sub-criterion is expressed in available air volume (cubic meter per hour (CMH)) per metric tonne (MT) of produce. As per NHB standard [4], multi-commodity storage facilities must provide 170 CMH per MT of produce for quick cooling based on chamber capacity. After reaching the desired storage temperature, the airflow should be reduced to 34-68 CMH per MT with a VFD and control system to maintain a temperature variation of less than ±1°C throughout storage. For pre-cooled produce, the airflow can range from 67-100 CMH.

Pre-cooling (pull-down) time per batch (1% weightage): This sub-criterion pertains to the time required to pre-cool or pull down a batch of produce before storing it in a cold room or pre-cooling room. The pre-cooling time per batch can vary depending on several factors, such as the size of the batch, the produced incoming temperature, the desired storage temperature, and the efficiency of the pre-cooling system. Pre-cooling time can vary from a few hours to overnight, depending on the specific situation. The pre-cooling time per batch also sets the limit for the maximum number of batches that can be pre-cooled daily, thus determining the overall pre-cooler handling capacity. According to the NHB standard [4], most fresh fruits and vegetables (except apples and carrots) require a pre-cooling time of 4-6 hours to achieve 7/8th cooling.

Thermal energy storage (1% weightage): This sub-criterion pertains to the process of storing excess refrigeration capacity during off-peak periods and using it during on-peak periods to reduce energy consumption and costs. Thermal energy storage (TES) in cold rooms is achieved by using thermal storage systems such as ice banks, chilled water storage tanks, or phase change materials (PCMs). TES helps reduce the overall size of the refrigeration system, thereby reducing first cost, the peak energy demand of cold storage facilities, decreasing energy costs, and leading to more efficient operations. In the case of off-grid solar power systems, TES could be charged during the daytime and released during the nighttime.

Total overall connected load (1% weightage): This sub-criterion pertains to the overall connected load for the facility, which will affect the fixed demand charges that the local distribution company will levy on the facility. This is important to consider when designing the refrigeration system for a cold storage facility to avoid incurring financial penalties for overshooting the contract demand with the electricity distribution company.

4. Renewable Energy Integration (7% weightage)

Solar photovoltaic integration (4% weightage): This sub-criterion pertains to the integration of solar photovoltaic (PV) systems into the cold storage facility to generate electricity using solar energy. The size and type of PV system depend on the intended use and can be categorized as off-grid or grid-interactive. Off-grid PV systems typically incorporate battery energy storage, while grid-interactive systems can be classified as gross-metered or net-metered. The gross-metered system exports all the generated power to the grid, while the net-metered system uses the power generated by the PV system to offset the facility's electricity consumption and export the excess power to the grid.

Biomass (3% weightage): This sub-criterion pertains to the use of biomass as a renewable energy source for powering absorption technology-based cooling systems in cold storage facilities. Biomass refers to organic matter, such as wood, crop residues, or animal waste, that can be burned to produce heat or electricity. Biomass is a sustainable and cost-effective approach, as it is a renewable energy source that can often be locally sourced. However, the quality and type of biomass fuel, as well as the efficiency and emissions of the combustion or gasification process, must be carefully considered before deciding to use it as a primary source of energy.

5. Monitoring and Controls (7% weightage)

Remote monitoring and energy/environmental management controls (7% weightage): This subcriterion focuses on the remote monitoring system and the data it should store to track and monitor the performance of the system effectively. The data should be timestamped every one or two minutes and may include indoor and ambient temperatures and RH, power and energy parameters of each machine, TES charge level, solar PV power parameters and energy parameters, battery bank power parameters, compressor low-pressure and high-pressure monitoring, and ethylene levels in each room. The parameters should be customized based on the specific requirements of the project. The NHB standard [4] recommends using sensors, controllers, indicators, temperature scanners, centralised indicators, and PLC systems for regulating various parameters, depending on the cold storage capacity. However, the standard does not provide clear guidelines for smaller capacity pre-cooling and staging cold rooms.

6. Supply, Installation, Testing, and Commissioning (SITC) (7% weightage)

SITC timeline (3% weightage): This sub-criterion covers the timeline for the supply, installation, testing, and commissioning of the cold storage system, including the supply of necessary materials, equipment installation, system testing, and commissioning. The timeline must be well-planned and include milestones and deadlines to ensure timely project completion. The NHB standard [4], pertaining to SITC in general and not the SITC timeline specifically, recommends that the plant shall be installed, tested, and commissioned as per IS 660 [9] or ASHRAE Std. 15 [10].

Commissioning checklist (4% weightage): This sub-criterion covers the development of a commissioning checklist tailored to the project's specific needs. The checklist should include activities such as fine-tuning the system to optimize performance, training end-users on safe and effective operation, conducting final acceptance testing to ensure project requirements are met, and documenting the commissioning process in detail. The purpose of the commissioning checklist is to ensure that all the necessary steps are taken to ensure the proper operation of the equipment and system to meet the project requirements.

7. Operations and Maintenance (O&M) (7% weightage)

Warranty (manufacturing defects and workmanship) (2% weightage): This sub-criterion pertains to the warranty provided by the manufacturer or seller of the equipment or system being procured. The warranty may cover manufacturing defects, workmanship issues, or both and may be limited to certain product components. The warranty terms may also require the user to follow specific maintenance and usage instructions to qualify for the warranty.

Training of the local operations team and O&M manual (2% weightage): This sub-criterion pertains to the training of the local operations team and the creation of an O&M manual. The local team must be trained on how to operate and maintain the system or equipment efficiently. The O&M manual should include detailed instructions and guidelines on maintenance schedules, troubleshooting procedures, and safety guidelines. With proper training and a comprehensive O&M manual, the local team can ensure smooth operation, reduce downtime, and avoid equipment failure or maintenance issues.

After-sales services (3% weightage): This sub-criterion pertains to the after-sales services provided by the manufacturer or vendor to customers after the sale of a product or service. These services may include technical support, maintenance, repairs, and warranty support. The quality and availability of after-sales services can significantly impact the ongoing operation and maintenance of the equipment or system.

The suggested evaluation framework is applicable to the selection of cold rooms and pre-cooling facilities designed to manage perishable fruits and vegetables of varying storage/handling capacities, ranging from a few MT to thousands of MT. However, when considering Controlled Atmosphere (CA) storage, which is commonly used for the long-term storage of perishables like apples, pears, kiwis, cabbage, etc., an additional layer of O_2 and/or CO_2 regulation becomes necessary in conjunction with the specifications outlined in this assessment framework [11]. In terms of temperature and RH storage conditions, the evaluation framework can cover a range of 0°C to 21°C and 65% to 100% RH for various fruits and vegetables as specified in the NHB standard [4]. The applicable storage duration can also vary from short-term (7 to 10 days) to medium or long-term storage, extending up to 10 months.

Results and Discussion

The authors applied the framework to assess vendors of cold-chain equipment for pre-cooling and staging cold rooms, focusing on a specific use case selected through a comprehensive process. Surveys were conducted on forty-eight Farmer Producer Companies (FPCs), and field visits were made to nine of them to identify potential use cases that could assist farmers in reducing losses, maintaining produce quality, and increasing the value of their produce through cold-chain solutions. The research team evaluated four potential use cases to showcase energy-efficient and eco-friendly cold rooms. After careful consideration of the sufficiency principles, they selected one use case that would best suit the farmers' needs by defining the optimum requirements that were neither too large nor too cold.

The team then met with cold-chain equipment manufacturers to learn about their offerings. Subsequently, a Request for Proposal (RfP) was created that outlined the technical specifications required for the selected use case and the evaluation framework. The RfP was sent to fifteen vendors, out of which nine submitted their proposals. Each product was evaluated against the framework's criteria, which included technical and financial considerations. Two rounds of evaluation were performed as the RfP process aimed to solicit vendors' best available technology, with no detailed specifications in the first round. After the first round of evaluation, six vendors were shortlisted out of nine for final vendor presentations with project partners. The final round of evaluation for the six shortlisted vendors was conducted with additional information on design conditions and minimum performance specifications. During the detailed specification collection process, it was observed that there is a lack of emphasis on energy efficiency and sustainability in the business-as-usual scenario, indicating an awareness gap on both the demand (users) and the supply (vendors) sides. Through the entire evaluation process, vendors were better informed about energy efficiency and sustainability criteria for designing and developing cold-chain solutions. Three vendors were chosen based on the final technical evaluation, and their selection was supported by customer testimonials, further enhancing the technical and financial assessment. Based on the overall evaluations, one vendor was selected to deploy a pre-cooling cold room and two staging cold rooms. The vendor used innovative thermal energy storage, solar energy, low-GWP refrigerant, and energy-efficient cold room envelopes, all of which are environmentally friendly.

The authors contend that energy-efficient and renewable-powered cold-chain solutions with low operational expenditures will be more viable and sustainable for farmer groups, which the evaluation framework duly acknowledges. Further, the evaluation framework's focus on sufficiency and efficiency will contribute towards building energy-efficient, climate-friendly cold-chain infrastructure with a lower carbon footprint than business-as-usual (BAU) systems. The effectiveness of the cold rooms in reducing produce loss, increasing produce value, and the cold rooms' energy performance will be monitored for 3-6 months post-installation.

Integrating the evaluation framework in government schemes

The central government provides financial support for the development of cold rooms and other cold-chain infrastructure through schemes under the Mission for Integrated Development of Horticulture (MIDH) [12] and the Agricultural and Processed Food Products Export Development Authority (APEDA) [13]. The MIDH and APEDA schemes mandate adherence to NCCD protocols and standards [6]. Additionally, the MIDH scheme states that assistance will be provided for cold rooms that are energy efficient. While the NCCD protocols and standards provide a reference data sheet on technical criteria to consider while selecting a cold room, there are no criteria for energy efficiency.

The evaluation framework presented in this paper includes cold room specification criteria over and above those provided by NCCD, particularly criteria to assess energy efficiency and clean energy supply, such as refrigeration system efficiency at different operating conditions, variable speed operation principle, thermal energy storage, and renewable energy integration, among others. The authors suggest that this evaluation framework may be considered for inclusion in NCCD guidelines for cold rooms to enable applicants for MIDH, APEDA, or other government schemes to assess the energy efficiency of solutions from different vendors.

Further, the administrators for MIDH, APEDA, and other government schemes can mandate such a comparison between vendor solutions and disburse funds for the most energy-efficient, climate-friendly cold room. As more data on the energy performance of cold rooms is made available, and standards and labelling for cold rooms come into effect, scheme administrators can also mandate minimum performance standards for each criterion in the evaluation framework presented in this paper and disburse funds only for solutions that meet the mandated minimum performance standards. Government schemes for cold-chain can draw lessons from existing agriculture schemes for irrigation, such as PM-KUSUM [14] and state-level Agriculture Demand Side Management (AgDSM) [15] programs that mandate the use of energy-efficient and renewable energy technologies such as solar pumps and 5-star-rated energy-efficient pumps.

Conclusion

This paper's proposed evaluation framework can be vital for FPCs, wholesale and retail businesses dealing with horticultural produce, food processing industries, and state agriculture marketing boards. It can assist in analyzing various vendors' cold room solutions and making informed decisions about procuring and deploying energy-efficient, environmentally friendly cold rooms. Moreover, integrating this framework into government subsidy programs for cold rooms could encourage the growth of sustainable cold-chain infrastructure, as opposed to traditional business-as-usual technologies.

Along with the evaluation framework, the authors have also developed a monitoring system to track the efficiency and energy performance of assessed and subsequently deployed cold rooms. This gathered data will serve as an essential resource for establishing energy performance benchmarks for cold rooms.

Further, to enhance energy efficiency and sustainability in cold-chain equipment, a standards and labelling (S&L) program for cooling and refrigeration equipment, particularly for pre-cooling and staging cold rooms, could be instituted. The evaluation framework in this study and the energy performance data from field-deployed cold rooms could be instrumental in formulating this S&L program. The program should focus on reducing both direct and indirect emissions from cooling equipment, stressing energy efficiency and the appropriate choice of refrigerants [16].

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