International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 • Website: www.ijfmr.com • Email: editor@ijfmr.com

Cold Chain Infrastructure in India and its Future Potential

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Abstract
India is one of the largest producers of perishable commodities, yet a significant portion of produce is lost due to inadequate cold chain infrastructure. The lack of packhouses, pre-cooling units, reefer vehicles, and multi-commodity cold storages severely affects the efficiency of supply chains. This study evaluates the current status of cold chain infrastructure in India and identifies the major challenges affecting its development. The paper uses a simplified Best–Worst Method (BWM) approach to prioritize key barriers—economic, policy, technological, and operational. Results indicate that economic challenges carry the highest impact, followed by policy gaps. The study highlights the urgent need for integrated cold chain development to reduce post-harvest losses, improve quality, and unlock India's future potential in the perishable supply chain sector.

Chapter 1: Introduction

Background

India, as the world's second-largest producer of fruits and vegetables, faces significant challenges due to the lack of adequate cold chain infrastructure. Despite producing over 310 million tons of fruits and vegetables in 2020-21 [1], the country experiences substantial post- harvest losses of perishable commodities. Current estimates suggest that the existing cold storage infrastructure in India can only accommodate around 11% [2] of the total perishable produce, highlighting a critical gap in the cold chain network.

The significance of establishing a reliable cold chain network in India is paramount. This infrastructure is instrumental in minimizing financial losses for farmers, guaranteeing food security, and delivering top-notch produce to local and global markets. The cold chain functions as a regulated logistics system that entails maintaining precise conditions such as temperature, humidity, atmosphere, and packaging to efficiently preserve and transport perishable goods.

Research has shown that a well-functioning cold chain infrastructure can greatly help address the difficulties faced by farmers and food producers, particularly small-scale farmers who often have limited income. It is estimated that India loses around The annual loss of INR 926 billion (US$14.33 billion)[3] because of post-harvest losses is a huge financial burden to India's economy. Besides that, the country daily loses $19.4 million [4] of crops value to rejected at the farmgate and distribution delays which are harmful to the environment owing to toxicity, water pollution, and greenhouse gases.

According to a study on India's cold chain infrastructure, the country's cold storage facilities are mainly designed to store individual commodities, such as potatoes and grains, with less than 10% of agricultural produce being processed through a cold chain. This highlights a significant shortage of cold chain infrastructure, particularly in the initial stages from the farmgate to post-harvest handling, which affects post-harvest management. This shortage extends across various value chains, including fruits, vegetables, dairy, fish, and meat.

To address these challenges and harness the future potential of cold chain infrastructure in India, a comprehensive analysis is essential. Understanding the status of cold chain infrastructure, identifying key focus areas for improvement, and exploring opportunities for growth and development are crucial steps towards enhancing the efficiency and effectiveness of the cold chain network in the country.

Problem Statement

Presently, the Indian refrigerated transport system lag far behind the backbone of the needed supply chains. Only less than 10% [3] of agricultural products are processed through the cold chain within the country, with most of the other parts of the facilities designed for single commodities like grains and potatoes. If parts of a cold chain infrastructure (CCI) are in place, however, an integrated system is hard to find in general value chains. Still surprisingly, CCI stands a gap as the first 'mile' is behind with a 99% [5] gap and the result is the same regarding the dairy sector due to an 80% [5] gap and 70% [5] in fishing.

Aim and Scope of the Study

This research is designed to present holistic facts about existing cold chain transport in India and to provide projections for future development. Specifically, the study will:

Determine the status in Cold Chain sector by monitoring all the key value chains provision fruits & vegetables, dairy, fish & meat.

Develop the framework which will enable us to determine and measure the shortcomings of the CCI in place and the demand for such an infrastructure for the needs of these value chains up to the year 2030 [5].

The scope of the studies includes the assessment of CCI requirements in the foremost fruits, vegetables, dairy, fish, and also in beef in the chill. mild-chill, and frozen categories. The milk distribution is excluded because of the already established supply-chain networks of its but the dairy products that are on a higher value range, such as ice cream are considered under the frozen food category.

Objectives of the Study

The primary goals of this research endeavor are as follows:

A thorough evaluation of how perishable food goes to waste across the nation by assessing the consumption patterns.

We need to evaluate the current supply and demand for the cold chain sector in the city to determine the points of sale, infrastructure, and system gaps.

Hence, it streamlines the cold chain sector's strategic role by integrating it into policy formulation and interventions for the development and improvement of the poor cold chain sector.

By addressing these objectives, the study strives to contribute to the development of an efficient and sustainable cold chain network in India. This network will play a pivotal role in fostering food security, mitigating post-harvest losses, and enhancing the livelihoods of farmers and stakeholders across the agricultural value chain.

Chapter 2: Review of Literature

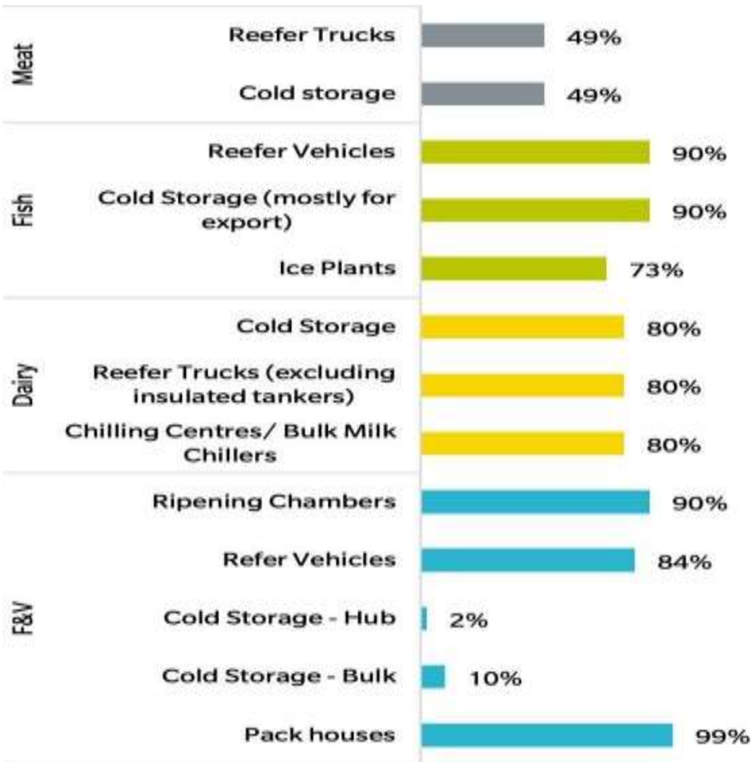
RO1: To assess current cold storage capacity and utilization rates across differentstates in India.

India with its huge herds of cows being the largest milk manufacturer worldwide, the largest food producer globally as well, has got a number of its population lives majorly depending on agriculture. India has solved the problem of food shortage because of the huge amount of agricultural production, however, the issue of malnutrition among the population persists, which is confirmed by the Global Hunger Index 2020 [5] report, where India is ranked 94th out of 107 countries and lags behind other neighbour countries like Bangladesh, Pakistan, and Nepal. Smallholders are the worst affected in the production and supply dimensions since they are the majority and continue to record low income levels. Reports show that 4.6-15.9% [10] of the foodstuff is either destroyed or lost annually along the supply chain.

The country goes through post-harvest loss worth of a staggering 926 billion INR (14.33 billion USD) [7]. On a daily basis, there is waste of farm goods worth of 19.4 million US dollars. This is because of the rejection at farmgate ad delays in the distribution process. These losses which heavily include toxic waste, water pollution, damaged ecosystems for a long time, hazardous air emissions into the atmosphere, greenhouse gas emissions and huge energy exhaustion have a terrible impact on the environment. Properly planned infrastructure of a CCI would help to solve the problems related to high investment expenses, lack of secure data system, and of weak infrastructure.

The cold chain system is a temperature-controlled logistics network that provides the transport of agro products or other fresh products under proper packaging. This system has the following storage conditions: temperature, humidity, and atmosphere. A cold chain developed and built appropriately will be able to prevent food losses and low carbon emissions which are connected to food waste, it will be vital component to make the food chain more sustainable. Moreover, cold chains undervalue of food security through partial control of food price fluctuations, risk elimination of food supply and seasonal shortages. The absorbed and erratic volatility by this mechanism avoids the price fluctuations that usually affect disadvantaged communities by falling into poverty and hunger, besides, also raising farmer salaries.

Table 1: CCI Gap Across Value Chains in 2020 [5]



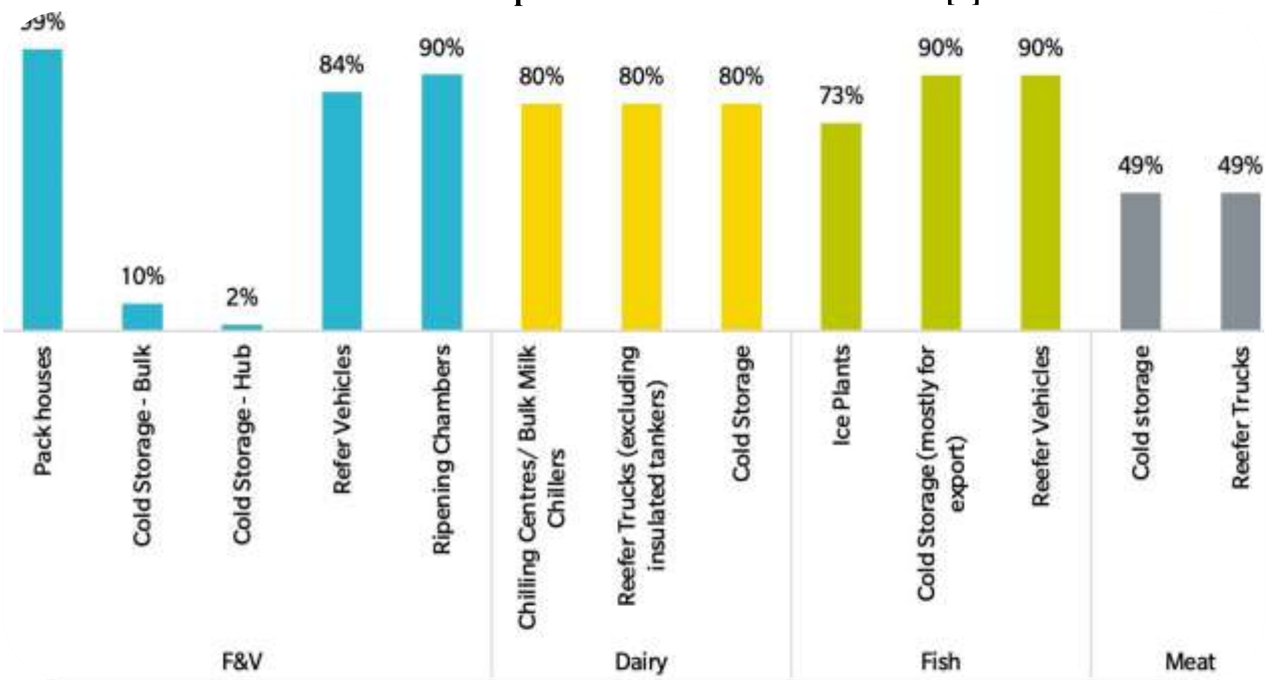
Cold Chain Infrastructure in India:

In India, as far as the cold chain infrastructure is concerned, the prominent facilities are mainly of bulk storage categories and used for single purposes like potatoes and grains. Thus, there is a need for increased awareness of the need for farmgate packhouses (pre-cooling units with cold rooms) and of the entire CCI system as their ignorance has been seen to make them have limited deployment and adoption rates. In 2015 the National Centre for Cold Chain Development (NCCD) [2], set up by the Government of India to give momentum to the cold chain established near 99% [57] gap in packhouses and 9% [5] gap in fresh fruits and vegetables (FFV) cold storage.

The FFV gap which was found during this survey conducted in the year of 2020 follows so that the arising emanates leading gaps in four value chains (as in Table). While the major CCI gaps in fish and fruit value chains are still very low, the meat sector has less gap than other sectors. This contributes to the vigor of the 90% informal meat market that operates in the form of slaughtering and proffering meat to consumers at the abattoir level of consumption immediately.

FFV's CCI mostly includes cold storage units for singular commodities like potatoes, onions, and grains, whereas there is a requirement of packhouses, reefer vehicles, and ripening chambers in the sector. In a marketing point of view, the milk sector is more organized with CCI components nearly 5-Score.

Table 2: CCI Gap Across Value Chains in 2020 [5]



VALUE CHAIN	CCI COMPONENT	REQUIRED (NOS.)	CREATED (NOS.)	GAP (%)
FFV	Packhouses	83,041	675	99%
	Cold Storage - Bulk	6,669	6,026	10%
	Cold Storage - Hub	231	225	2%
	Reefer Vehicles	70,035	11,000	84%
	Ripening Chambers	12,654	1,232	90%
Dairy	Chilling Centres / Bulk Milk Chillers	260,737	52,147	80%
	Reefer Vehicles *	8,733	1,747	80%
	Cold Storage	196	39	80%
Fish	Ice Plants	1,017	272	73%
	Cold Storage**	6,294	624	90%
	Reefer Vehicles	6,104	606	90%
Meat	Cold Storage	37	19	49%
	Reefer Trucks	1,776	910	49%

*excluding insulated tankers **mostly for export

Table 3: Estimated CCI Deployment and Requirements in India Across Different Value Chains (2020) [5]

Estimated needs and requirements for cold chain infrastructure (CCI) deployment across various value chains in India for the year 2020.

Evolution of Cold chain in India:

The conventional cold chain of India could be considered the network through which cold storage arrangements are done. Nevertheless, the NCCD [2] illustrates the cold chain as an environment-controlled supply chain meaning stocking and delivery activities that keep a product within a pre-designated range of ambient climate. It means a whole set of actions and processes that perishable goods are going through either from a source of farm raw material up to a production facility or a consumer end. It is not only the cold chain as a refrigerated storage and transport, but a supply chain that should be considered as a chain and a production site should be regarded as a point of origin, including horticultural packhouse, ice cream factory, an abattoir, or a vaccine manufacturing facility.

The cold chain in India started with the establishment of Kolkata's first cold room in the year 1892. Though the industry developed in an unscientific way but the scientific nature of the sector was started after independence through the introduction of the "Cold Storage Order, 1964" by utilising Section 3 of the Essential Commodity Act, 1955. By this Act, whole India was bought into its fold.

The West Bengal Act, the Uttar Pradesh Act, the Haryana Act, the Punjab Act, and etc. came after the Central Cold Storage Order with the following year of 1980. The Central Cold Storage Order 1980 was put in words by the Directorate of Marketing & Inspection (DMI) government of India, the Ministry of Agriculture. [4] During this period, the growth was moderate and quite attentive. The government of India changed the Central Cold Storage Law in May 1997 in harmony to breaking the shackles of policy of liberalization.

Post the unregulated period in 1997 (4), there has been a rapid establishment of cold storages all around India.

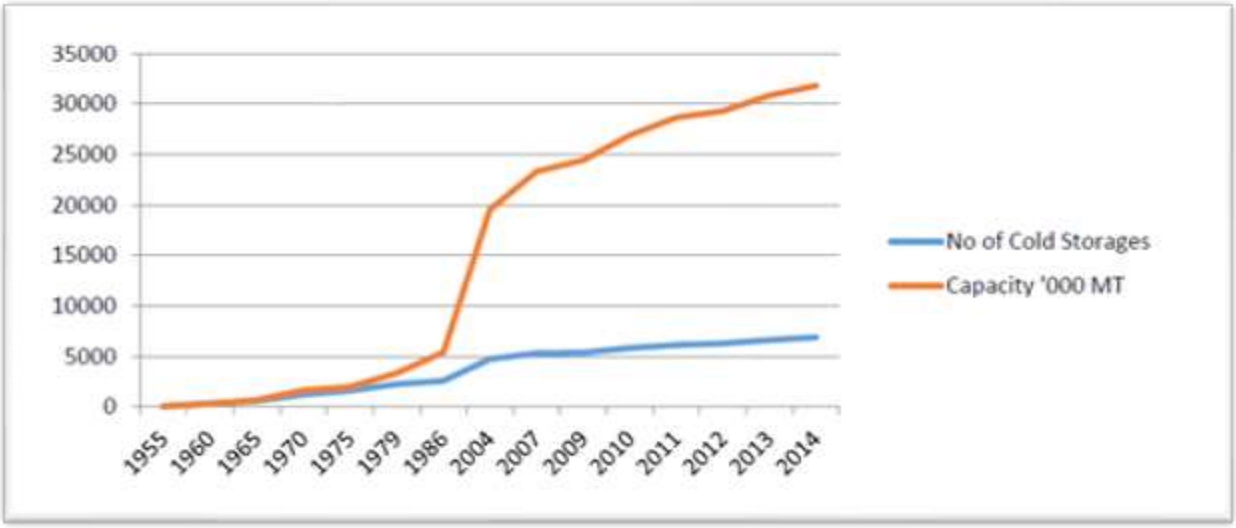


Table 4: Growth of cold storage in India [4]

The first step was taken by Government of India to maintain the speed of cold chain growth in the country by establishment of the High-Level Expert Committee (HLEC) in November 1998 under the chairmanship of Shri J N L Srivastava, former Secretary, Ministry of Agriculture and Cooperation. One of the committee's key functions was to upgrade cold stores and otherwise storage infrastructures in the country. They suggested the capacity of 12 lakh MT cold storages will be created during the 9th [8] Five year. Furthermore the National Horticulture Board provided capital investment subsidy for construction, expansion or the modernisation of the cold storage and storage facility for the horticultural produce along with the full implementation by the NABARD and DMI . This specific scheme served as the catalyst for the emergence of the standalone cold storage facilities all over the country. Moreover, the total population rapidly exceeded the growth of number of new units that were created after 2098 [8]. By the end of March 31, 2014, they [the cold storages] cumulatively had 6891 units with a cold storage size of 31.82 million tons [9]. However, cold chain was developed less in an integrated way, and the necessity for a scheme was called for.

In the year 2005-06, towards a mandate mode to uplift horticulture, National Horticulture Mission (NHM) was introduced along with the already prevailing Horticulture Mission for Northeast States and Himalayan States. As of 2013, the whole arms constituting the Department of Agriculture and Cooperation (DAC) for development of horticulture were consolidated under the heading Mission for Integrated Development of Horticulture (MIDH). After harvest, infrastructure development remained the core area of focus of MIDH. In October 2014, the Task Force on Cold Chain projects tasked the Department of Agriculture and the Department of Food Processing Industries to set up an additional 7.5 [9] m MT cold-chain capacity within the next 5 years. From the total 7.5mt, DAC has the ability to utilize 5 million MT under the MIDH and the Ministry of Food Processing Industries can require 2.5 million MT of the same capacity. The process needs to be planned to use an "end-to-end" approach in connecting the farm-gate to the consumers seamlessly.

M/s. the representative of cold stores was surveyed to give the baseline survey. The Hanasa Research for the National Horticulture Board [9] realized in 2013-14 as per DAC that the information on segment-wise share impounded from the respondents' answers to a census/survey were without being checked.

Those categories were based on respondents' statements, and cold store in-house multi-commodity might have been also resp.

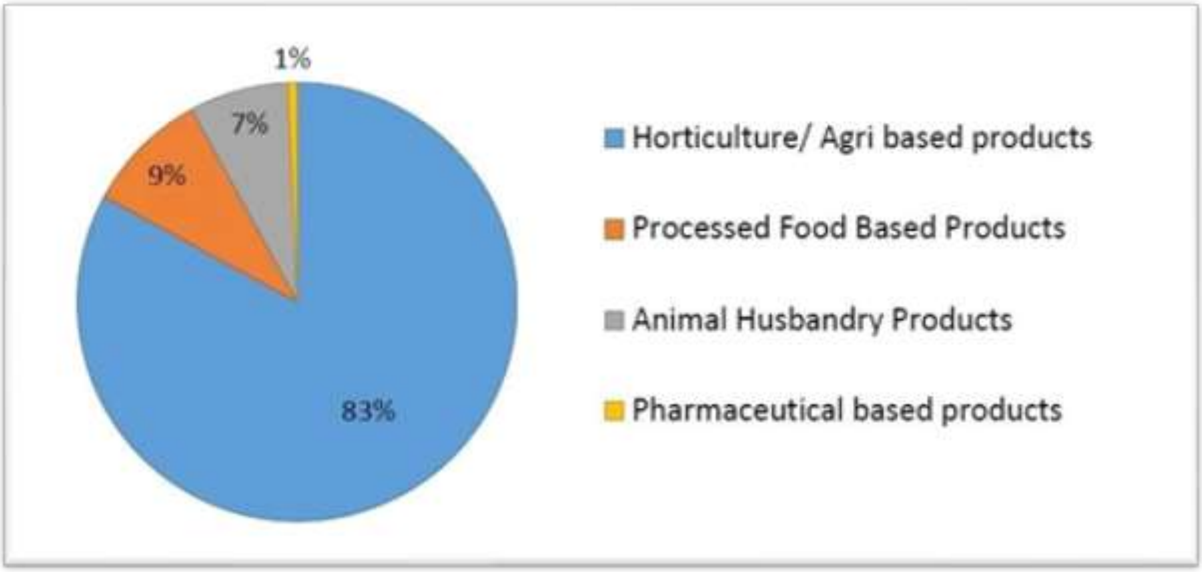


Table 5:Segment wise segregation of cold storage [4]

This survey revealed that 1219 [4] cold stores were permanently lost or inoperable with the remaining operable number of 2228 [2], making a total storage volume of 26.85 [3] million tons. The survey reveals that the majority cold storages help in transporation of products. At the same time, 79% still do not have the own transportation facility while packhouses are very limited for the integration into cold chain.

It is seen that while India has made progressive headway in the area of standalone cold storages, it will need to build up the whole cold chain along with other corresponding aspects of infrastructure. This research seeks to undertake and enlighten us on the infrastructure immense need to meet the domestic production that produces the current consumption of the urban population in India. It is obvious that the necessary measure that should be taken from modern packhouses and refrigerated transporting is the connection of producers and the markets. To be able to advance the integrated established cold-chain infrastructural sectors, the approach to such progress has to be holistic.

An earlier NCCD (National Centre for Cold Chain Development) report stated that in order to take care of a weekly fresh fruits and vegetables throughput of 2000MT [2] in a cold store [Hub] of size 5000MT [2], allied with an integrated packhouse development of 16 [2] units, there also needed to be an equal number of reefer vehicles. Actually the move towards more packhouses and refrigerated transport which was reflected in the figures for cold storage as it was only 18% of the investment in this chain [2]. Refrigerated transport sector is still a newcomer to the field of transportation in India. For instance, UK which had an approximately 5 million tons of cold storage space and had about 140,000 reefer vehicles in France, USA has about 80,000 reefer vehicles. According to studies, the fruits and vegetables in the U.S., which are 80-85%, channel through the cold chain. India’s reefer transportation negligibly utilized for domestic transportation of perishable goods.

It has further been observed that China also presently has a lack of reefers with an estimated 66,000 [1] reefers [1]. Further, the figures for India seem to suggest that there can be 10,000 or less [1] of refrigerated transport vehicles which are active and also not very reefer (thermal) trains. In addition to the private players which represent the major players, there a few operators in this field can make use of the full cold-chain solutions. In India, owing to the restored attention towards the development of the hinterlands, more notably through the implementation of PMGSY (Pradhan Mantri Gram Sadak Yojana) [1], the rural road network is taking shape and starting to physically feature in lives of the people living in the villages. For perishables, a control temperature system (reefer truck) however requires to collect the goods from the source handling points. Thus, packhouses that examine and pack the goods into the required order for market has become vital. This path seems incomplete without including a buffer inventory wherever it is needed to maintain food delivery. Therefore, cold storages come in handy to ensure the food supply chain runs smoothly. Overall, given that the operating routines and supply chains will be tight, then storage and prices will not be volatile and there will be minimal losses. Consequently, the packing centers, and particularly the packing houses, can operate differently by having the food processing units as secondary income sources, wherein they generate maximum returns from what is harvested.

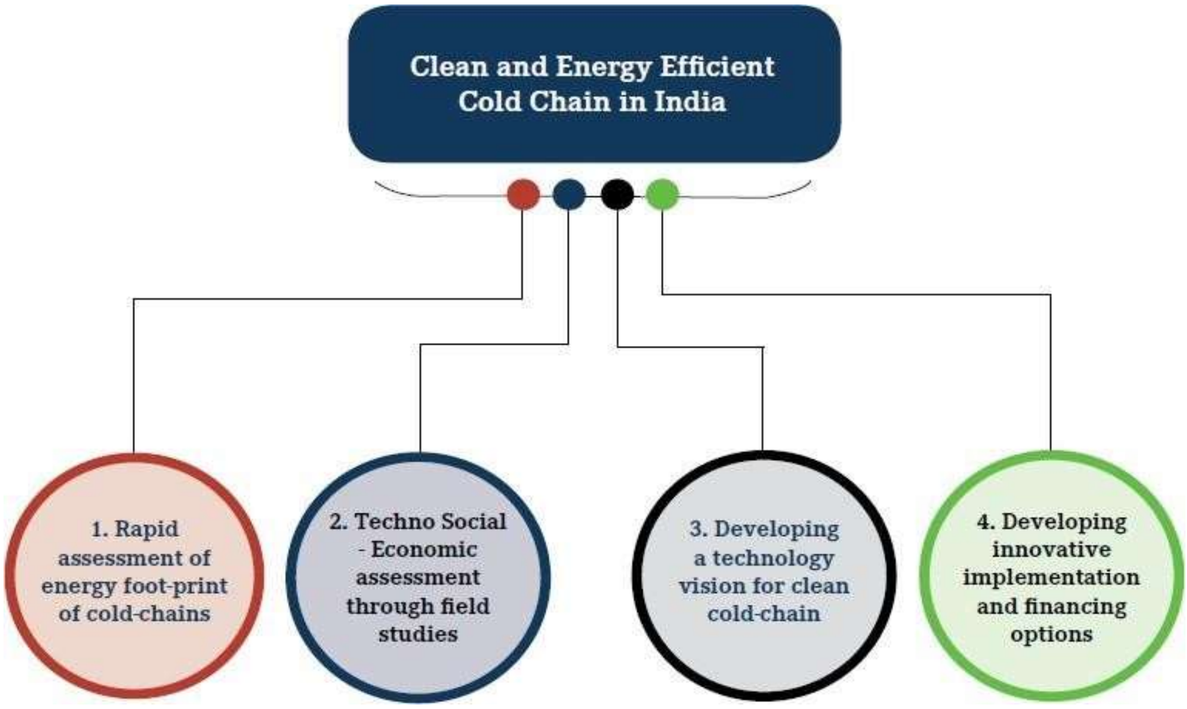


Table 6: Goals of the Study on Clean Cold-Chain in India [1]

Fresh Fruits & Vegetables (FFV)

To optimize the CCI market for fresh fruits and vegetables (FFV), it is advisable to transition the focus from a primary emphasis on cold storage to a broader consideration of other CCI components, particularly first-mile cold chain solutions such as packhouses.

By the time 2030 comes, the packhouse and reefer vehicles growths are estimated to double the farmers income at the rate of 51% and 34% each year respectively under the DFI scheme [11].

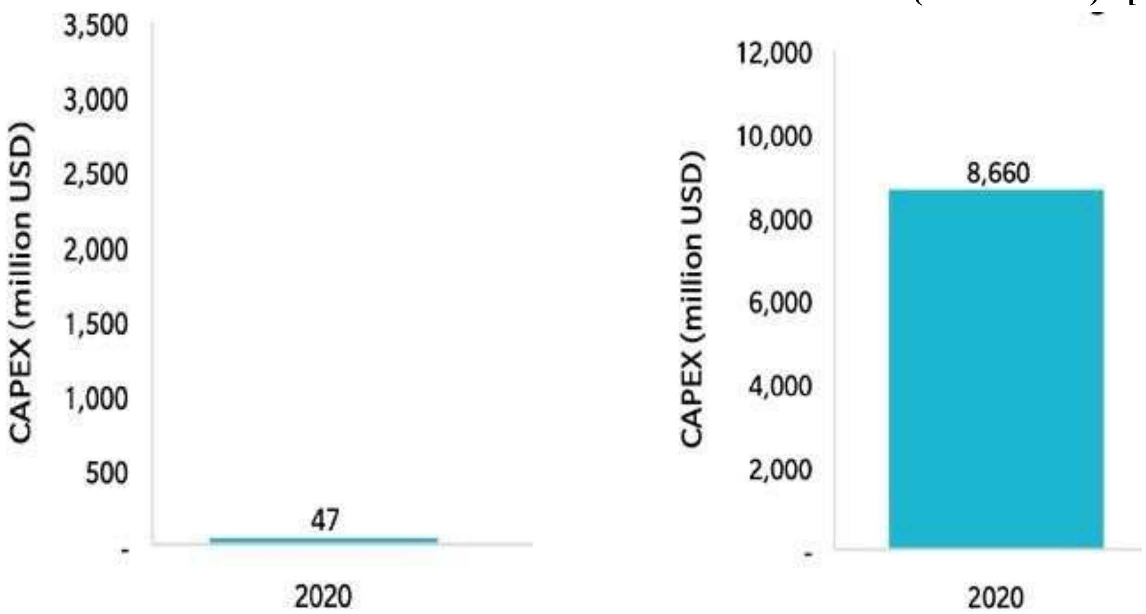
The introduction of packhouses is projected to spark transportation companies to utilize less reefer vehicles for the same output of seafood. It is estimated that two reefer vehicles for single packhouses, are to be factored [in the analysis], provided that the round-trip distance between the packhouse and to

the consumption center is longer than 450 km [12].
The historical growth rate of cold storage (bulk and hub types) in the country that has created over the past five years is around 2.7% [13]. The predicted percentage is going to drop to 2.5% (from 3.9% in 2017-2019 [13. The reason for the expected decline is the fact that the government initiated the program that aimed not only on developing cold storage but also on bridging the most severe infrastructural gaps and with time most of those gaps will be shorten.
According to the experts, the industry is forecasted to convert from single-crop cold storage into multi-crop units. These units usually have 365-days of utilization as compared to some units with seasons that only last a certain season. On the other hand, multi-functional units made a break-through and stood for 23% [14] in 2009 and now it is 30% [14].

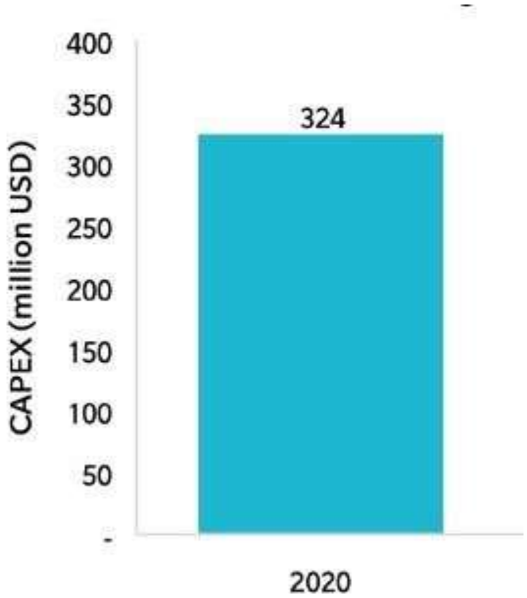
Year	Packhouses	Cold Storage -Bulk	Cold Storage -Hub	Reefer Vehicles	Ripening Chambers
Whole Market 2020	9.8	1307	45	2401	156
Whole Market Addressable 2020	7	915	32	1681	109
Whole Achievable Market 2020	0.1	827	31	264	11

Table 7: Market size, target market, and attainable market were evaluated in the vegetable value chain for various components of the cold chain infrastructure (CCI) on the basis of the CaaS model.[5]

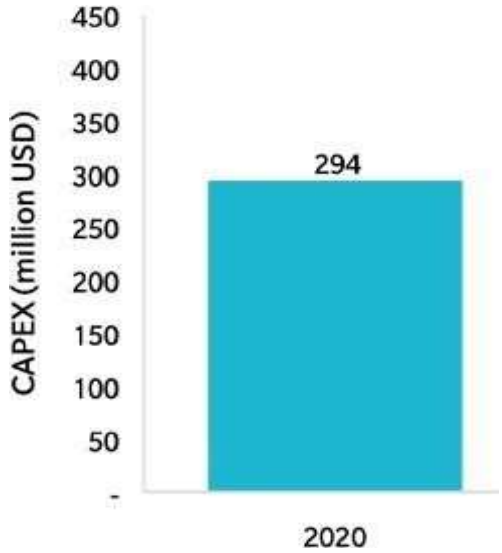
Table 8:CCI Market Size CAPEX Model Across FFV Value Chains (USD million): [5]



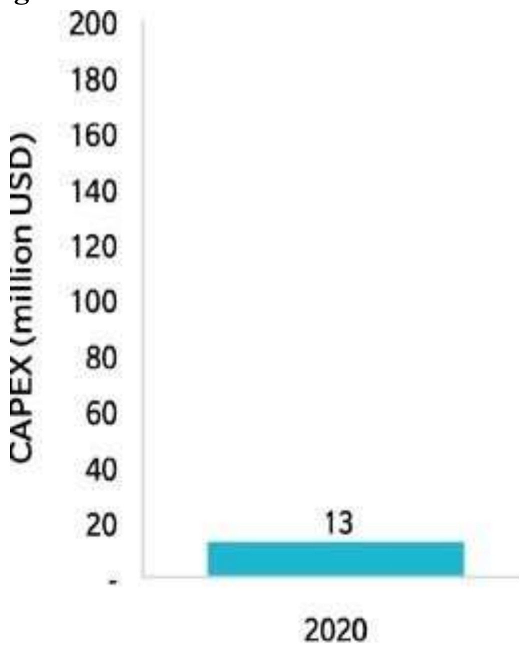
Packhouse Level **Cold Storage-Bulk**



Cold storage- Hub



Reefer Vehicles



Ripening Chambers

The average capacities per unit considered in this calculation include packhouses at 16 metric tons per day, cold storage (bulk and hub) at 5,000 metric tons each, reefer vehicles at 10 metric tons, and ripening chambers at 10 metric tons per day.

Dairy

Within the dairy industry, there's an increasing expectation that every dairy cooperative located in a remote or rural area will have bulk milk chillers (BMCs).

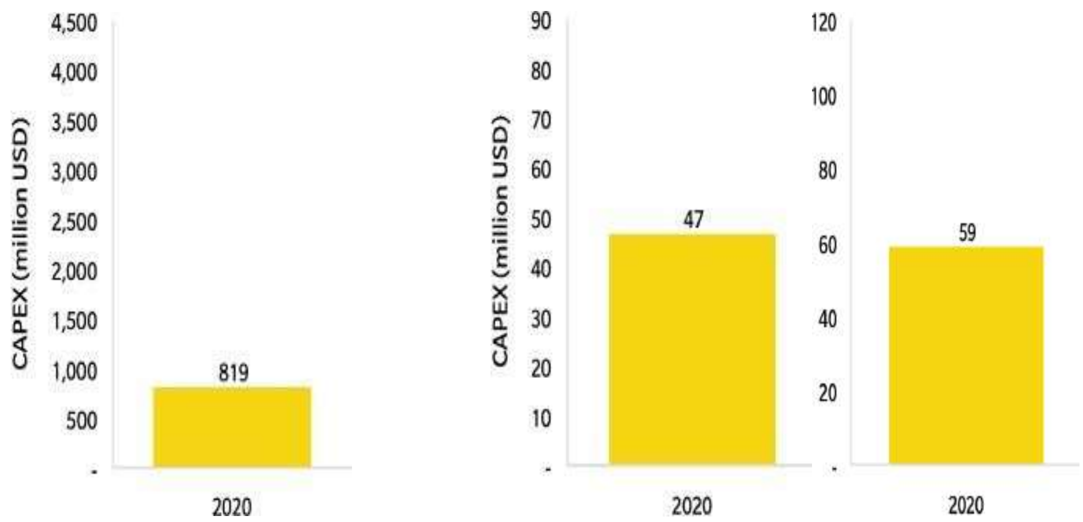
Dairy:

Year	Bulk Milk Chillers	Reefer Vehicles	Cold Storage	
Whole Market	2020	879	189	20

Whole Market Addressable	2020	853	183	20
Whole Achievable Market	2020	171	37	4

Table 9: Based on the CaaS model, the market size, addressable market, and attainable market for several cold chain infrastructure (CCI) components in the meat value chain have been calculated.[5]

Table 10: Across Dairy Value Chains, the CCI Market Size CAPEX Model (USD million): [5]



Bulk Milk Chillers **Reefer Trucks (excluding insulated tankers)**
Cold Storage

In this calculation, the average capacities per unit for chilling centers/bulk milk chillers, reefer vehicles, and cold storage facilities are 2,000 liters per day, 10 metric tons, and 5,000 metric tons, respectively.

Fish

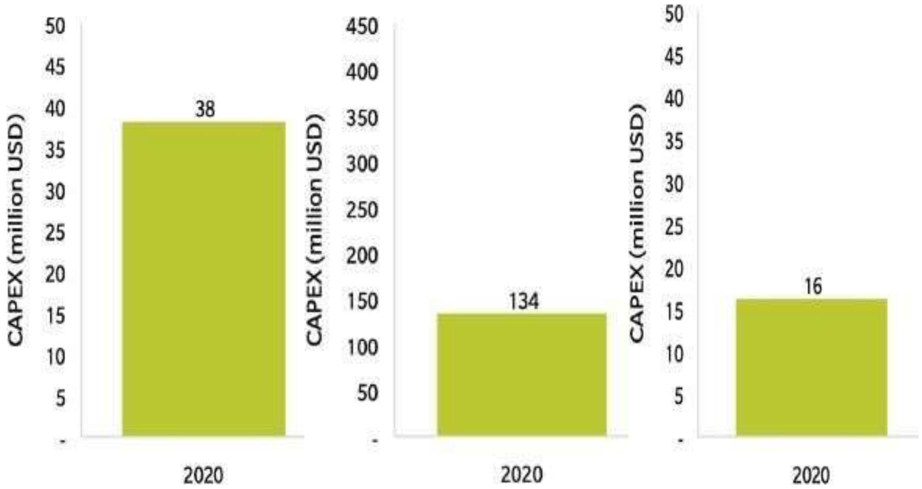
Meat and fish cold storage capacity are predicted to have grown at a compound annual growth rate (CAGR) of 11.3% [11] in the value chains that include them between 2014 and 2020. Since both the meat and fish sectors are focused on exports, these value chains are growing at a faster rate than fresh fruits and vegetables (FFV). The total capacity for cold storage of fish and meat has expanded from 0.8% to 1.8% in the last ten years [11].

Fish:

	Year	Ice Plants	Cold Storage(Mostly Exports)	Refer Vehicles
Whole Market	2020	137	249	174
Whole Market Addressable	2020	128	183	128
Whole Achievable Market	2020	34	18	13

Table 11: Based on the CaaS model, the market size, addressable market, and attainable market for several cold chain infrastructure (CCI) components in the meat value chain have been calculated.[5]

Table 12:CCI Market Size CAPEX Model Across Fish Value Chains (USD million): [5]



Ice Plants **Cold Storage Reefer**
Vehicles

In these calculations, the average capacities per unit for ice plants, cold storage facilities, and reefer vehicles are 40 metric tons per day, 700 metric tons, and 10 metric tons, respectively.

Meat

According to the CaaS market sizing, Table 13 shows the Whole Market, Whole Market Addressable , and Whole Achievable Market for various meat value chain components.

Meat:

	Year	Cold Storage	Refer Trucks
Whole Market	2020	6.2	38
Whole Market Addressable	2020	6.0	37
Whole Achievable Market	2020	3.1	19

Table 13: The CaaS model has been used to calculate the market size, addressable market, and attainable market for different cold chain infrastructure (CCI) components in the meat value chain. [5]

Table 14: Meat value chain CCI market size CAPEX model (USD million): [5]

Cold Storage **Reefer Trucks**

The average capacities per unit for cold storage and reefer trucks in the calculation are 5,000 metric tons and 10 metric tons, respectively. Vapors in the Current Cold Chain

The Cold-chain Development National Center (NCCD) [2] has outlined a set of recommended practices for the post-harvest handling of agricultural produce, as highlighted in the FAQs on Cold-Chain Development by Kohli (2015)

Type of Infrastructure	Infrastructure Requirement (A)	Infrastructure Created (B)	All India Gap (A-B)
Packhouse	70,080 nos.	249 nos.	69,831 nos.
Cold Storage (Bulk)	341,64,411 MT	318,23,700 MT	32,76,962 MT
Cold Storage (Hub)		9,36,251 MT	
Reefer Vehicles	61,826 nos.	9,000 nos.	52,826 nos.
Ripening Chamber	9,131 nos.	812 nos.	8,319 nos.

Source: All India Cold-chain Infrastructure Capacity Assessment of Status & Gap. New Delhi: NCCD, 2015

Table 15: Cold-chain Infrastructure gap [1]

Farm	Packhouse	Reefer Vehicle	Cold Storage/Ripening Chambers
• Managing timing of harvest with regard to logistics and market and holding life. • Least damage to produce as possible. • Close proximity to pre-conditioning centers – preferably within a 2-4 hour radius. • Use of post-harvest handling carriers to mitigate transport damage to pre-conditioning centre	• Sorting of produce by market value / destination • Curing of root & tuber crops (eg. red chillies, potatoes, cassava, yams, onions). • Washing or cleaning to remove field residues, pesticide or treat with fungicides. • Drying in case of washing and pre-cooling (where required). • Segregation/ Grading by size of produce for logistics handling before packaging. • Rapid pre-cooling for most fruit and vegetable crop types or slow cool down for vegetables such as onion and potato	• Dispatch from farm-gate to pre-conditioning centers, cold storage and retail points. • Pelletized stowage to destination storage using appropriate pelletized material handling equipment until dispatch to retail points.	• Rapid chilling or blast freezing of harvested animal product - meats or milk. • Short-term storage prior to onward dispatch to market centers or for long-term storage. • Divert low value or non-marketable surplus to food processing facilities • Farm-coding – record-keeping for traceability of produce. • Maintaining temperature and humidity parameters throughout the logistics chain. • Maintaining living (breathable and disease free) environment for fruits and vegetables, throughout the logistics chain. • Follow guidelines to avoid incompatibility, cross-contamination or tainting of produce

Table 16: Gaps in Existing Cold-Chain [1]

Table 17:State-wise Cold Stores Created [As on Mar'21] [2]

S/n	States and Union Territories	Count of Cold Storage Units	Size in MT
1	Andaman & Nicobar (UT)	2	210
2	Andhra Pradesh	404	15,77,828
3	Arunachal Pradesh	2	5,000
4	Assam	34	1,19,652
5	Bihar	303	14,06,395
6	Chandigarh(UT)	6	12,216
7	Chattishgarh	89	4,27,766
8	Delhi	97	1,29,857
9	Goa	29	7,705
10	Gujarat	560	20,30,873
11	Haryana	295	5,88,649
12	Himachal Pradesh	32	38,557
13	Jammu & Kashmir	28	64,769
14	Jharkhand	55	2,17,280
15	Karnataka	189	5,26,752
16	Kerala	197	78,355
17	Lakshadweep(UT)	1	15
18	Madhya Pradesh	260	10,97,168
19	Maharashtra	540	7,06,302.6
20	Manipur	1	2,175
21	Meghalaya	4	8,200
22	Mizoram	3	3,931
23	Nagaland	2	6,150
24	Odisha	111	3,26,639
25	Puducherry (UT)	3	85
26	Punjab	606	20,04,778
27	Rajasthan	154	4,80,032
28	Sikkim	2	2,000
29	Tamil Nadu	163	2,95,671
30	Tripura	13	39,181
31	Uttar Pradesh	2,176	1,36,33,039
32	Uttarakhand	28	84,545
33	West Bengal	502	59,01,925
Total		**6,891**	**3,18,23,700.6**

Table 18: State-by-state division of the cold-chain infrastructure need: [2]

State	Urban Populati on (2020-21)	% Share Popu-lation	Pack- house (No)	CS Bulk (MT)	CS Hub (MT)	Onion Storage (MT)	Ripening Chamber (MT)
Andhra Pradesh	18428602	4.46	3124	489195	41730	551273	4070
Arunach al	354419	0.09	60	6705	803	--	78
Assam	4774459	1.15	809	61185	10811	--	1054
Bihar	13008947	3.15	2205	5094524	29458	155936	2873
Chhattis garh	6670958	1.61	1131	498724	15106	--	1473
Delhi	17718674	4.29	3003	--	40122	--	3913
Goa	1002786	0.24	170	--	2271	--	221
Gujarat	28523771	6.90	4835	2174886	64590	305066	6299
Haryana	9998498	2.42	1695	217754	22641	305686	2208
HP	722662	0.17	122	304511	1636	--	160
J&K	3807726	0.92	645	899220	8622	--	841
Jharkhand	8710072	2.11	1476	5228	19723	--	1923
Karnata ka	25886395	6.26	4388	151695	58618	809817	5717
Kerala	19831340	4.80	3361	968	44906	--	4379
MP	21658925	5.24	3671	1818134	49045	1130550	4783
Maharashtra	54543414	13.19	9245	34200	123509	3063522	12045
Manipur	943761	0.23	160	2925	2137	--	208
Meghala ya	651738	0.16	110	17228	1476	--	144
Mizoram	623469	0.15	106	7508	1412	--	138
Nagaland	676818	0.16	115	7142	1533	--	149
Odisha	7583316	1.83	1285	288328	17172	--	1675
Punjab	11227754	2.72	1903	1667984	25424	--	2479
Rajastha n	18558887	4.49	3146	11370	42025	337343	4098
Sikkim	210234	0.05	36	2145	476	--	46

TamilNadu	37817826	9.15	6410	109005	85635	--	8351
Telangana	12806317	3.10	2171	248130	28999	442517	2828
Tripura	1161198	0.28	197	5925	2629	--	256
Uttar Pradesh	48414644	11.71	8206	10565506	109631	72945	10691
Uttarakhand	3410752	0.82	578	65208	7723	273893	753
West Bengal	31729218	7.67	5378	9409081	71848	--	7007
UT Others	340	--	4539	--	443		
All-India Urban	**413461936**	**70080**	**34164411**	**936251**	**7448545**	**91306**	

RO2: Identify key challenges and opportunities in cold chain development:

Challenges	**Producer (Farmer/FPO/FPC)**	**CCI Manufacturer/Operator**
Policy	• Lack of awareness of existing government policies to supportCCI • No additional incentives for the farmer/trader to cold store their produce	• Delayed and complex process for claiming subsidies • Lack of standards promoting energy efficient CCI technologies • Lack of financial support for small-capacity CCI
Technological	• Lack of awareness of post-harvest cooling requirements and technologies, and the benefits of cold chain • Little use of modern harvesting techniques and machinery	• Lack of knowledge of how to identify cooling needs and appropriate cooling technology • Lack of modern, affordable CCI • Lack of standards to guide purchasing decisions • Lack of knowledge about standards for equipment and materials used in CCI, including renewable energy equipment • Lack of expertise in operating CCI in rural areas
Economic	• High investment costs • Unaffordability of investing in or using CCI services • Lack of awareness of available financing support • Lack of access to financing due to perceived credit risk	• Questionable economic viability due to seasonal changes in production volumes • High investment costs • High cost of land procurement, and unavailability of land near farmgate

	• Uncertain ROI for CCI owners	• Lack of government incentives for standalone cold storage • High cost of power • Uneven demand distribution, resulting in the concentration of CCI in clusters
Operational	• Unreliable power supply and uneven access to grid electricity • Lack of knowledge of operating CCI for specific products, leading to inefficient utilisation • Lack of connectivity, access to consumer markets and market linkages • Lack of standard operating procedures, maintenance, and installation procedures	• Lack of skilled manpower to operate CCI • Irregular and uncertain power supply • Low utilisation rates, leading to lower revenue • Inadequate demand aggregation, leading to low CCI utilisation

Chapter 3: Research Methodology

Best Worst method

An MCDM problem includes a lot of criteria ($c_1, c_2, c_3, \dots, c_n$), many alternatives ($a_1, a_2, a_3, \dots, a_m$) and for each alternative with respect to each criterion there is a score ($p_{11}, p_{12}, p_{13}, \dots, p_{mn}$). Thus we can represent an MCDM problem with this matrix:

$$A = \begin{array}{c|cccc} & c_1 & c_2 & \dots & c_n \\ \hline a_1 & p_{11} & p_{12} & \dots & p_{1n} \\ a_2 & p_{21} & p_{22} & \dots & p_{2n} \\ \dots & \dots & \dots & \dots & \dots \\ a_m & p_{m1} & p_{m2} & \dots & p_{mn} \end{array} \quad [15]$$

An MCDM problem's primary goal is to identify the optimal option with the greatest possible total score (V_i). The following formula (Keeney & Raiffa, 1993) illustrates how to utilize an additive weighted value function as one of the simplest ways to determine the total score for each alternative:

$$V_i = \sum_{j=1}^{n} w_j p_{ij} \quad [16]$$

The weight of each criterion w_j is determined by using the best-worst method (BWM) in this case (Rezaei, 2015). Given that we know the score of every alternative with respect to each criterion p_{ij}, it is easy to calculate the overall score.

The BWM method involves the following steps to calculate the vector $w = \{w_1, w_2, w_3, \dots, w_n\}$:

Step 1. Define a set of criteria

In this step, the choice-maker ought to outline a set of criteria (c1, c2, c3,..., cn) with a view to be used to come to a decision about the alternatives.

Step 2. Define the best and the worst criterion

At this factor, the decision-maker is requested to decide the pleasant and the worst criterion primarily based on their significance.

Step 3. Define the preferences of the best criterion over the other criteria

In this step, the decision-maker determines a vector called Best-to-Other (BO), which is as follows:

AB = (aB1, aB2, aB3,..., aBn) [17]

in which aBj is the preference of the great criterion B over the criterion j, and its cost is an integer quantity in the range of one to 9. Note that aBB = 1.

Step 4. Define the preferences of all criteria (j) over the worst criterion W

In this step, the decision-maker determines a vector called Other-to-Worst (OW), which is just like the following vector:

AW = (a1W, a2W, a3W,..., anW)^T [18]

Where ajW is the choice of the criterion j over the worst criterion W, and its cost is an integer range inside the range of one to nine. Note that aWW = 1.

Step 5. Search for the optimal solution

This phase requires defining the best weights for criteria (vector W). This means finding a solution that minimizes maximum gaps between obtained weights and decision-maker's opinion. According to ajW which is preference of criterion j over criterion W (or criterion B over criterion j) by decision maker, or in other words, ajW = preference j/preference W (aBj = preference B/preference j). Because we get to know preferences of all criteria while determining their weights wj = preference j can be said. So, it follows that wB/wj = preference B/preference j. The point of BWM is to find such a weight vector where for every j |wj/wB - ajw| and |wB/wj - aBj| are minimized as absolute gaps among them. In order to do this, mini-max formulation is provided then followed by linear model development (Rezaei, 2016).

The final linear model of BWM is as follows:

min ξL

s.t.

|wB - aBjwj| ≤ ξL, for all j [19]

|wj - ajWwW| ≤ ξL, for all j

n

Σ wj = 1

j=1

wj ≥ 0, for all j

The problem (5) has a unique solution, and via solving it, we can reap the premiere weights (w*) and ξL*. We can do not forget ξL* as a trademark of the consistency of the comparisons. Lower values ofξL*represent higher consistency.

Chapter-4: Result and Discussion

BWM Analysis

Challenges	Producer (Farmer/FPO/FPC)

Policy (PC)	Lack of awareness of existing government policies to support CCI
	No additional incentives/subsidies for the farmer/trader to cold store their produce
	Lack of strict regulations on promoting energy efficient CCI
Technological (TC)	Lack of awareness of post-harvest cooling requirements and technologies, and the benefits of cold chain
	Little use of modern harvesting techniques and machinery
	Lack of technological innovation and expertise
Economic (EC)	High investment costs
	Unaffordability of investing in or using CCI services
	Lack of awareness of available financing support
	Lack of access to financing due to perceived credit risk
	Uncertain ROI for CCI owners
Operational (OC)	Unreliable power supply and uneven access to grid electricity
	Lack of knowledge of operating CCI for specific products, leading to inefficient utilization
	Lack of connectivity, access to consumer markets and market linkages
	Lack of standard operating procedures, maintenance, and installation procedures

Key Challenges in CCI	**Determined as Best by managers**	**Determined as Worst by managers**
Policy Challenges (PC)		2, 3
Technological Challenges (TC)		
Operational Challenges (OC)		1, 4, 5, 6
Economic Challenges (EC)	1, 2, 3, 4, 5, 6	

Table 1: Main criteria challenges comparison

BO	**PC**	**TC**	**OC**	**EC**
Best criterion: **(Economic Challenges)**	2	5	8	1

OW	**Worst criterion: Operational Challenges (OC)**
PC	4
TC	2
OC	1
EC	8

Table 2: Weights of Main Challenges

Main Challenges	**Weights of Main Challenges**
Policy Challenges (**PC**)	0.392
Technological Challenges (**TC**)	0.130
Operational Challenges (**OC**)	0.071
Economic Challenges (**EC**)	0.407

Table 3: Pairwise comparison of policy challenges for case company

BO	**PC_1**	**PC_2**	**PC_3**
Best criterion: **PC_3**	8	3	1

OW	**Worst criterion: PC_1**
PC_1	1
PC_2	4
PC_3	8

Table 4: Pairwise comparison of technological challenges for case company

BO	**TC_1**	**TC_2**	**TC_3**
Best criterion: **TC_1**	1	3	8

OW	**Worst criterion: TC_3**
TC_1	8
TC_2	4
TC_3	1

Table 5: Pairwise comparison of economic challenges for case company

BO	**EC_1**	**EC_2**	**EC_3**	**EC_4**	**EC_5**
Best criterion: **EC_2**	3	1	2	8	4

OW	**Worst criterion: EC_4**
EC_1	3
EC_2	8
EC_3	4
EC_4	1
EC_5	2

Table 6: Pairwise comparison of operational challenges for case company

BO	**OC_1**	**OC_2**	**OC_3**	**OC_4**
Best criterion:	1	7	4	9

OC_1				

OW	**Worst criterion: OC_4**
OC_1	9
OC_2	2
OC_3	3
OC_4	1

Main Challenges	**Weights of Main Criteria**	**Sub-criteria Challenges**	**Weights of Sub-Criteria Challenges**	**Global Weights**	**Rankings**
Policy Challenges (PC)	0.392	PC_1	0.098	0.038	1
		PC_2	0.336	0.132	13
		PC_3	0.567	0.222	15
Technological Challenges (TC)	0.13	TC_1	0.677	0.088	11
		TC_2	0.246	0.032	7
		TC_3	0.077	0.010	4
Operational Challenges (OC)	0.071	OC_1	0.658	0.047	8
		OC_2	0.099	0.007	3
		OC_3	0.174	0.012	5
		OC_4	0.069	0.005	2
Economic Challenges (EC)	0.407	EC_1	0.174	0.071	10
		EC_2	0.376	0.153	14
		EC_3	0.256	0.104	12
		EC_4	0.063	0.026	6
		EC_5	0.13	0.053	9

Discussion:

Table 1: Main criteria challenges comparison

This table summarizes the key challenges in CCI adoption as identified by managers/experts. It shows that under Policy Challenges (PC), sub-criteria 2 and 3 were determined as the worst challenges. For Technological Challenges (TC), no specific sub-criteria were highlighted as best or worst. However, for Operational Challenges (OC), sub-criteria 1, 4, 5, and 6 were identified as the worst challenges. Interestingly, all sub-criteria under Economic Challenges (EC) were determined as the best challenges by the managers/experts.

Table 2: Weights of Main Challenges

This table provides the weights assigned to the main challenges based on the BWM analysis. Economic Challenges (EC) have the highest weight of 0.407, followed by Policy Challenges (PC) with a weight of 0.392. Operational Challenges (OC) have the lowest weight of 0.071, while Technological Challenges (TC) have a weight of 0.130.

Table 3: Pairwise comparison of policy challenges for the case company

This table shows the pairwise comparison of the sub-criteria under Policy Challenges (PC). The sub-criterion PC3 (Lack of strict regulations on promoting energy efficient CCI) emerges as the best criterion with a weight of 8, while PC1) is identified as the worst criterion with a weight of 1.

Table 4: Pairwise comparison of technological challenges for the case company

In this table, the sub-criterion TC1 is identified as the best criterion with a weight of 8, while TC3 (Lack of technological innovation and expertise) is determined as the worst criterion with a weight of 1.

Table 5: Pairwise comparison of economic challenges for the case company

This table presents the pairwise comparison of the sub-criteria under Economic Challenges (EC). EC2 emerges as the best criterion with a weight of 8, while EC4 is identified as the worst criterion with a weight of 1.

Table 6: Pairwise comparison of operational challenges for the case company

In this table, the sub-criterion OC1 is identified as the best criterion with a weight of 9, while OC4 is determined as the worst criterion with a weight of 1.

Main Criteria Weights:

The weights assigned to the main criteria (Policy Challenges: 0.392, Technological Challenges: 0.13, Operational Challenges: 0.071, Economic Challenges: 0.407) provide insights into the relative importance placed on each of these challenge areas. In this case, Economic Challenges and Policy Challenges have the highest weights, suggesting that they are considered the most critical areas overall.

Sub-Criteria Challenges:

Within each main criteria category, the sub-criteria challenges are further broken down and assigned weights. These weights reflect the perceived significance of each specific challenge within its broader category.

For example, under Policy Challenges, PC3 has the highest weight of 0.567, indicating that it is seen as the most crucial policy challenge. Conversely, PC1 has the lowest weight of 0.098, suggesting it is viewed as a relatively less critical policy challenge.

Similarly, under Technological Challenges, TC1 (weight: 0.677) emerges as the most important technological challenge, while TC3 (weight: 0.077) is considered the least significant.

Global Weights and Rankings:

Global Weights take into account both the main criteria weights and the sub-criteria weights, providing an overall assessment of the relative importance of each sub-criteria challenge across the entire framework.

By ranking the sub-criteria challenges based on their Global Weights, the table highlights the most pressing issues that require immediate attention and resource allocation.

For instance, PC1, ranked 1st with the highest Global Weight of 0.098, would be the top priority sub-criteria challenge to address. This could be due to a combination of Policy Challenges being a highly weighted main criteria category (0.392) and PC1 having a relatively high weight (0.25) within that category.

Conversely, PC3, despite having the highest weight (0.567) within the Policy Challenges category, is ranked 15th overall due to its lower Global Weight of 0.222. This suggests that while PC3 is important within its specific category, other sub-criteria challenges from different categories are considered more critical when evaluated across the entire framework.

Implications and Use Cases:

This weighted and ranked framework can be instrumental in various decision-making processes, such as:

1. **Resource allocation:** The rankings and Global Weights can guide the distribution of resources (financial, human, or otherwise) to address the most pressing sub-criteria challenges first.
2. **Strategic planning:** The framework can inform the development of long-term strategies and action plans by prioritizing the sub-criteria challenges based on their relative importance.
3. **Risk assessment and mitigation:** By identifying the highest-ranked sub-criteria challenges, organizations can proactively address potential risks and implement mitigation measures.
4. **Performance evaluation:** The framework can be used to assess the effectiveness of existing initiatives or policies by evaluating their impact on the prioritized sub-criteria challenges.
5. **Stakeholder communication:** The clear hierarchy and weighting system can facilitate transparent communication with stakeholders, justifying the allocation of resources and the prioritization of specific challenges.

Analysis:

Best-Worst Method (BWM) analysis conducted in this research provides valuable intellect into the critical challenges hindering the widespread adoption of cold chain infrastructure (CCI) in India. By systematically evaluating and prioritizing the main challenges and their sub-criteria, the analysis offers a roadmap for stakeholders and policymakers to address these barriers effectively.

Notably, the analysis highlights that economic challenges pose the most significant hurdle, with a weight of 0.407 among the main challenges. Within this category, the sub-criteria of the prohibitive cost of investing in or utilizing (EC2, weight: 0.153) and the lack of awareness regarding available financing support (EC3, weight: 0.104) emerge as the top concerns. These findings underscore the need for concerted efforts to reduce the high investment costs associated with CCI and to improve access to financing options for stakeholders, particularly smallholder farmers and small-scale producers.

Potential strategies to address these economic challenges include the development of blending arrangements, such as ppp, investment funds, and accessible credit facilities tailored to the unique needs of the agricultural sector. Additionally, raising awareness about existing government subsidies, tax incentives, and financing support programs can empower stakeholders to make informed decisions and leverage available resources for CCI adoption.

Policy challenges, with a weight of 0.392, also emerged as a significant barrier. The absence of stringent regulations promoting energy-efficient CCI (PC3, weight: 0.222) was identified as the most critical sub-criterion within this category. This finding underscores the need for policymakers to introduce comprehensive regulatory frameworks and incentives to encourage the adoption of energy-efficient CCI practices. Such policies can not only drive the adoption of sustainable CCI but also contribute to the overall reduction of carbon emissions and environmental impact associated with the agricultural sector.

Furthermore, the analysis highlights the importance of addressing operational challenges, albeit with a lower weight (0.071) compared to economic and policy challenges. The unpredictable power source (OC1, weight: 0.047) emerged as the most pressing sub-criterion within this category. Ensuring a stable and reliable power supply is crucial for the effective operation of CCI facilities, particularly in rural and remote areas where access to grid electricity may be limited.

While technological challenges (weight: 0.130) were not identified as the most critical barrier, insufficient knowledge of post-harvest cooling needs and technology options (TC1, weight: 0.088), should not be overlooked. Capacity-building initiatives, such instructional programs and sensitization drives, particularly the lack of education and understanding regarding post-harvest cooling requirements and technologies, as well as the potential advantages of adopting cold chain practices, among farmers and producers is a significant challenge.

By addressing these challenges through a comprehensive and coordinated approach, India can unlock the full potential of CCI, leading to reduced post-harvest losses, enhanced food security, and improved livelihoods for farmers and stakeholders across the agricultural value chain. Collaborative efforts among policymakers, industry stakeholders, financial institutions, and research organizations are essential to develop and implement effective strategies tailored to the unique needs and challenges of the Indian agricultural sector.

Chapter-5: Conclusion

The findings of this comprehensive study unveil the pivotal obstructions impeding the widespread embracement of cold chain infrastructure (CCI) in India. Through a methodical evaluation and prioritization of the primary hurdles and their intricate sub-components, the analysis illuminates a strategic pathway for decision-makers and stakeholders to surmount these barriers effectively.

Notably, economic impediments emerge as the most formidable obstacle, commanding the highest precedence among the main challenges. Within this domain, the exorbitant investment costs associated with CCI adoption and the dearth of awareness regarding available financing avenues crystallize as the paramount concerns. Addressing these economic impediments necessitates the conception of innovative financing mechanisms, fostering public-private collaborations, establishing investment funds, and rendering accessible credit facilities tailored to the distinct necessities of the agricultural sector. Concurrently, augmenting cognizance about extant government subsidies, fiscal incentives, and financing support programs can empower stakeholders to make informed decisions and leverage available resources judiciously.

Furthermore, the study accentuates the criticality of policy interventions, underscoring the dearth of stringent regulations and incentives to promote energy-efficient CCI practices as a pressing priority. Policymakers must orchestrate comprehensive regulatory frameworks that incentivize the adoption of sustainable CCI practices, thereby contributing to the overarching objective of reducing carbon emissions and mitigating the environmental impact associated with the agricultural sector.

While operational challenges, such as uneven access to grid electricity bear a relatively lower weight, their resolution remains imperative for the effective deployment of CCI facilities, particularly in remote and rural locales. Concurrently, capacity-building initiatives and awareness campaigns must be undertaken to edify stakeholders, especially farmers and producers, the multifaceted benefits of embracing CCI practices: the diverse advantages of adopting CCI methodologies.

By addressing these multifarious challenges through a coordinated and comprehensive approach, India can unlock the immense potential of CCI, decrease in post-harvest losses, Minimization of post-harvest losses, Diminution of post-harvest losses, Curtailment of post-harvest losses. Collaborative endeavors involving policymakers, industry stakeholders, financial institutions, and research organizations are imperative to develop and implement efficacious strategies tailored to the unique needs and challenges of the Indian agricultural sector.

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