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Research Article

A computational analysis of energy-efficient evaporative cooling systems vs conventional cold storage for onion preservation: Hybrid approach

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ABSTRACT

The rising energy and sustainability challenges in post-harvest storage systems have accelerated the need of low-cost, energy-efficient cold storage. This study presents a comparative analysis of two-stage indirect-direct evaporative cooling (EC) system with conventional cold storage (CS) for preserving 25 tons of onions under hot and humid climatic conditions. A heat load-based design methodology was employed to develop the EC structure, incorporating sensible and latent heat calculations, product respiration, infiltration. Computational Fluid Dynamics analysis was performed to analyze air movement pattern and temperature distribution inside onion storage structure. The design of EC was validated by the EvapCal software and experimental result. All the results are in good agreement with each other. The EC system, with a total investment cost of ₹3.36 lakh, has reduced heat load by 77.2% (from 102,000 BTU/hr to 23,328 BTU/hr) and daily energy consumption by 76.14% (from 150 kWh/day to 35.79 kWh/day), corresponding to a projected annual operational cost of ₹1.49 lakh, similar to CS but with much lower dependency on energy. The EC system also had higher air exchange rates (86 vs 40 ACPH) and lower spoiling rates (15 vs 25%). The EC technique showed 82% energy savings, increased shelf life and lower decay and sprouting rates in experimental experiments backed by CFD predicted airflow and temperature profiles. The EC approach offers a highly sustainable, low-cost solution suitable for small-scale farmers. The computational analysis confirms that EC systems offer energy-efficient alternative for hot and humid climate conditions.

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INTRODUCTION

Agriculture field is mainstay of the Indian budget. It has 18% contribution in India's Gross Domestic Product. It is major source of livelihood for almost half of the population. The agricultural sector supports pastoral development. Agriculture field satisfies food and employment need of growing population. It also plays a key role in international trade. India is major exporter of onions. Onion belongs to Amaryllidaceae family. Its scientific name is Allium cepa L. Onion is having global importance. It is grown extensively in different climatic settings[1]. India is the second largest producer of onion. Onion is cultivated over an area of 16% and production of 10% in the world (FAOSTAT, 2022) [2-4]. One of the most consumed vegetables in India, they are an important condiment in Indian cuisine [5]. Onions are appreciated not only for their use in the kitchen but also for medicinal aids [6-10]. Onions are garnered generally in Kharif (October-November, ~20% of total yield), Late Kharif (January-February, ~30%) and Rabi (April-June, ~50%). (Kharif and Rabi are seasonal farming patterns in India, Kharif being the season crop and Rabi the winter crop.) It is during the rabi season that most of the farmers grow onions. Onion's average monthly domestic consumption is about 1.1 million tonnes [11]. The inadequate and untenable storage systems leads to seasonal supply gluts and high price volatility [12,13]. The onion supply chain in India suffers from huge post-harvest losses due to poor storage infrastructure and management procedures [14]. More than 40% of post-harvest losses are estimated to be due to inappropriate handling, sprouting, decay, microbiological deterioration and lack of storage facilities [15]. Microbial degradation contributes to about 15-20% of the losses. Post-harvest rotting of onion causes an estimated loss of INR 11,000 crore (~1.32 billion USD) to the Indian economy annually [16-18]. Good storage conditions are important to minimise these losses. The optimal temperature for storing onions is 25-27 °C and the relative humidity is 65-70% which helps to minimize moisture loss, prevent sprouting and maintain the marketable quality of the bulbs [19-21]. Good ventilation also enhances storage by limiting the development of hot patches and water accumulation [22,23]. Storage problems are more severe in tropical and subtropical areas like as India where high temperature and humidity increase the difficulties in storage [24]. The cold storage is maintained at 0°C and 65-70% relative humidity to ensure good preservation. Significant initial investment, high maintenance expenses required to achieve this condition. Ventilated warehouse designs and aerated storage systems also offer advantages but may still be inadequate under peak seasonal loads [12,23]. Conventional onion storage suffers from considerable deterioration because of poor ventilation, uncontrolled temperature, and excessive energy usage. Various storage systems and architectures have been investigated by researchers to overcome these problems.

A thorough assessment of available literature done in order to identify the gaps and to guide further developments in onion storage and post-harvest preservation. The past studies analysis allows us to evaluate existing storage designs, cooling techniques, and energy-saving approaches deployed and proposed in distinct environmental conditions. It also facilitates in assessing the performance of the emerging technologies like CFD based airflow optimization, indirect and direct evaporative cooling, solar based cold storage and IoT based monitoring. Moreover, a holistic analysis helps one to understand the ground realities of small and marginal farmers' problems and ensures that the offered solutions are affordable and scalable. Lawande et al. used ventilated buildings for onion storage and recommended structures having dimension 9.14 m*15.24 m*3.65 m. These buildings have two rows. The walking space of 1.21 m kept between them. The authors also noted that the storage structure length should not exceed 15.24 m. Bottom and top ventilated buildings provide better results than other arrangements [12]. Ventilated structures for onion storage can enhance shelf life [25]. During April-May period, onions are produced in large quantities, and due to insufficient storage facilities, they must be sold immediately, causing farmers to earn lower profits because of the abundance of onions at that time. A shortage of onions occurs from November to January because no cultivation takes place, leading to price increases in the market [26]. Tripathi et al. suggested dual row, bottommost ventilated building having dimension of 9.9 m*4.75 m*2.25 m, with 4 m central height. The storage capacity of 31 tons for normal atmospheric conditions to minimize the losses [27]. Priyan et al. in their studies showed that 80% of marginal farmers did not have storage facilities, due to which they could not preserve onions after harvest. Air-cooled technology could be a feasible alternative for these farmers [28]. To increase profits and prevent post-harvest waste, implementation of a customized, self-sufficient and cost-effective cold storage system near the farmers' field using Android-powered technology for effective monitoring is aimed. This novel strategy not only extends the shelf life of perishable foods but also empowers farmers to have more control over their produce by allowing them to sell at optimal pricing rather than under pressure in peak harvest time [29]. Hourani et al. undertook an interesting journey to find out a successful desiccant dehumidification system which was smartly combined with a two-stage evaporative cooling system that worked perfectly in hot and humid climates[30]. The unique hybrid air conditioning solution proposed by them led to a significant 16.15% reduction in energy consumption and an excellent 26.93% reduction in water consumption than single-stage evaporative cooling system with the same thermal comfort [30]. Swati et al. studied the economic aspect of onion preservation and concluded that onion growers should use new storage techniques after harvesting to increase their income [31]. As per CTARA IIT Bombay, the design and development of an integrated curing and storage structure for onions is to reduce losses by around 80%-90% [32] Sipho et al. investigated the effects of IAC + EC in establishing a favorable storage climate for temperature and relative humidity (RH) in tomato fruits compared to ambient storage. Their research shows that evaporative cooling is excellent in maintaining the optimal temperature and RH for storage, and can potentially save roughly 75% of energy [33]. Jing Lv et al. performed flow analysis to analyze the temperature at different locations, air circulation, along with energy usage. They observed that evaporative cooling cycle utilizes 80% lesser electricity than normal VCC refrigeration system [34]. Sullivan L et al. conducted an experiment utilizing a computational fluid dynamics (CFD) model to chill palletized polyline kiwifruit bundles with forced air. This led to greater chilling uniformity, which might improve the product's quality during refrigeration [35]. A CFD investigation of a tiny desiccant-evaporative HMX was performed by Cue et al. The HMX integrated the advantages of regenerative indirect evaporative cooling with liquid desiccant dehumidification, enabling the product air inside the HMX to be chilled and dried at the same time [36]. Pinar et al. conducted detailed analysis of evaporative cooling technologies and their applications in buildings, highlight the benefits of evaporative cooling in terms of cost and energy savings [37]. Porumba et al. concluded evaporative cooling minimizes the energy consumption of air conditioning systems and recommends around 80% energy savings for fresh air cooling compared to RVCC [38]. Bogdan et al. provide useful information on indirect evaporative cooling (IEC). Their results show that this cooling technique has a great potential for future growth because of its very low energy consumption and excellent efficiency for a wide range of applications with a negligible global warming impact [39]. Nik et al. studied dynamic behaviour of air inside potato storage. The latest advances in physical modelling, simulation and management of ventilated bulk storage facilities are fostering the use of CFD airflow analysis to enhance understanding [40]. Dani et al. looked at genetic features in onions such as decaying, nascent, and weight loss using fast curing (FC) technology. The testing period is of 9 days after harvesting at 30°C and 98% RH. They suggested gamma irradiation technology to reduce losses during storage [41]. Mishra et al. developed an affordable, smart, and photovoltaic cold storage system. It consists of inland split air conditioner. Their discoveries reveal that the solar-powered refrigeration system is a cost-effective, simple, and energy-savvy alternative. Their research advocates for the application of IoT-based technology for monitoring agricultural storage [42]. Serap et al. looked at fluid flow analysis of two different cold storage operated at ambient conditions and showed that it gives better validation than experimental results [43]. Vala et al. investigated the validation of the evaporative cooling system through CFD analysis. The maximum reduction of air temperature was 22.10 °C to 25.80 °C during the performance test under the best operating conditions [44]. Bhamare et al. suggested the use of direct evaporative cooling for hot and desert climatic conditions[45]. Priyam et al. presented a detailed study on the development of an adaptive comfort model for buildings utilizing evaporative cooling in the composite climate of India [46]. Literature study indicates that post-harvest light treatment significantly affected quercetin levels in onions, where blue light resulted in the highest quercetin concentrations [47]. Furthermore, the use of UV light sources effectively doubles the quercetin concentration by enhancing the levels of both quercetin and quercetin glucoside in onions post-exposure [47]. Table 1 compare traditional cold storage and evaporative cooling system.

Table 1. Assessment of conventional cold storage and evaporative cooled storage

Operational Parameter	Cold Storage	Evaporative Cooling system
Humidity	65–70%	65–70%
Capital investment	High	Low
Temperature range	~0 °C	25–27 °C
Operational cost	High (continuous electricity consumption)	Low (can use solar energy)
Energy consumption	High	75–80% less than cold storage
Suitability for rural/ small farmers	Limited (cost prohibitive)	High (affordable and scalable)
Spoilage Reduction	Excellent (long shelf life, low spoilage)	Good (significantly better than ambient, but less than cold storage)
Environmental impact	High (due to electricity and refrigerants)	Low (eco-friendly)
Climate dependence	Works in all climates	Best in hot and dry climates;
Precision in maintaining conditions	Very high (tight control over temperature/RH)	Moderate (dependent on ambient conditions)
Technology adoption in India	Low among small farmers due to cost	Growing interest for small-scale applications
Research gaps	Well studied, but lacks CFD-based airflow optimization for onion storage	Limited studies using CFD for airflow and temperature distribution

Extensive research in the open literature highlights the importance of post-harvest onion storage technologies for reducing spoilage, improving shelf life, and stabilizing market prices. The ventilated warehouses, aerated bins and conventional cold storages have focused on temperature distribution airflow dynamics, and humidity management and energy consumption [13,27,29,35,43]. Despite the growing study on onion storage systems, there are certain important gaps still remain in dark. Firstly, abundant research on either cold storage or evaporative cooling but very few have provided a direct comparison of both the systems under the same operational settings for Indian climate. Secondly, previous studies have mostly focused on energy efficiency or economic analysis, but there is a lack of deep insight into airflow uniformity, temperature gradients inside the storage areas, and their impact on post-harvest onion preservation. Third, many experimental research were based on empirical measures that are typically expensive, time-consuming, and limited by spatial resolution. Technologies like as direct and indirect evaporative cooling, solar-powered refrigeration, IoT-enabled monitoring and CFD-based airflow optimisation have showed promise in improving the storage performance. Computational fluid dynamics (CFD) modelling has been successfully used to other crops such as potatoes, tomatoes and kiwi fruit [33,35,40]. To bridge these gaps, this study uses CFD-based simulations to comprehensively analyse airflow and temperature distribution in evaporatively cooled and traditional cold storage setups built specifically for onion storage in the climatic conditions of India. The work is targeted at affordability and scalability for marginal farmers and is intended to offer practical insights for the development of sustainable and cost-effective storage options.

The present work intends to compare two-stage indirect-direct evaporative cooling system performance over the cold storage. The investigation involves manual design calculations, CFD simulations, EvapCal software modelling and experimental endorsement for a storage term of 30 days. The EvapCal program ensures the trustworthiness of the CFD model which provides independent estimates of cooling performance unique to evaporative systems. The benchmarking process also involved cross-comparison with experimental results. This hybrid methodology enhanced the accuracy of the simulations and provided a robust basis for evaluating and optimizing the proposed evaporative cooling system in comparison with conventional cold storage. The primary objective is to assess the capability of evaporative cooling structures in reducing energy consumption, minimizing sprouting, weight loss, and maintaining product quality, to provide sustainable alternative for post-harvest storage in energy-constrained regions.

MATERIALS AND METHODS

Methodology

Figure 1 show methodology adopted for present study. The methodology is specifically structured to systematically investigate airflow distribution, spatial temperature distribution and humidity, energy efficiency, and post-harvest product quality. The workflow developed based on existing CFD modeling practices, evaporative cooling system design standards, and post-harvest storage protocols to ensure simulation accuracy and experimental validation.

Storage Structure

The experimental setup is one kind of storage structure. It has dimension of 9.144 m*4.26 m*4.26m as shown in figure 2. It has sloped roofing on both sides. The entire volume of the structure is around 165.941 m^3. The wall of storage is made from 60 mm thick polyurethane foam (PUF) panels. The side wall hight is 1.21 m, and the middle height is 4.26 m from the ground. The top roofing is composed of 50 mm PUF panels. Floor is constructed using plain cement concrete coated with 0.1 m thick PUF insulation. The structure equipped with wooden stacks. Each stack has dimension of 2.43 m*1.21 m*1.52 m. These stacks are made of wooden floorings of 0.15 m width and 0.018 m thickness. Each row contains three stacks with 0.60 m gap and 0.30 m clearance from walls and floor for better ventilation. The structure comprises two rows of stacks with 1.21 m aisle between the rows for access. This design can hold 25 tonnes of onions in economical way.

Polyurethane foam (PUF) insulation possesses superior insulating properties, hence, commonly used in storage development. Thermal resistance of the material is an important selection factor. Thermal resistance to heat is the ability to restrict heat. The thermal resistance value determines insulation quality. The warmth of the base is encased by polyurethane foam insulation. The ground level base is made of portland cement concrete with 0.1 m of PUF insulation on top of it. PUF has low heat conductivity of 0.024 kcal/m/h °C, which makes it best insulation material. The insulated walls made from cold-rolled close-annealed sheets of 60 mm thickness. Roof insulation with 50 mm PUF roofing panel.

Heat Load Estimation

Accurate estimation of heat load is critical for designing both cooling systems. Cold storage heat load calculations make sure the refrigeration unit is sized (in tons of refrigeration) to maintain desired storage temperature despite outside and inside heat gains. The entire cooling load includes the heat transfer rate through insulated wall, ceiling and floor, the product load due to initial cooling of onions, heat of respiration, infiltration, lighting and equipment load through door openings and air leaks. The other hand, the heat load calculations for the evaporative cooling system are mostly related to the sensible heat gains from

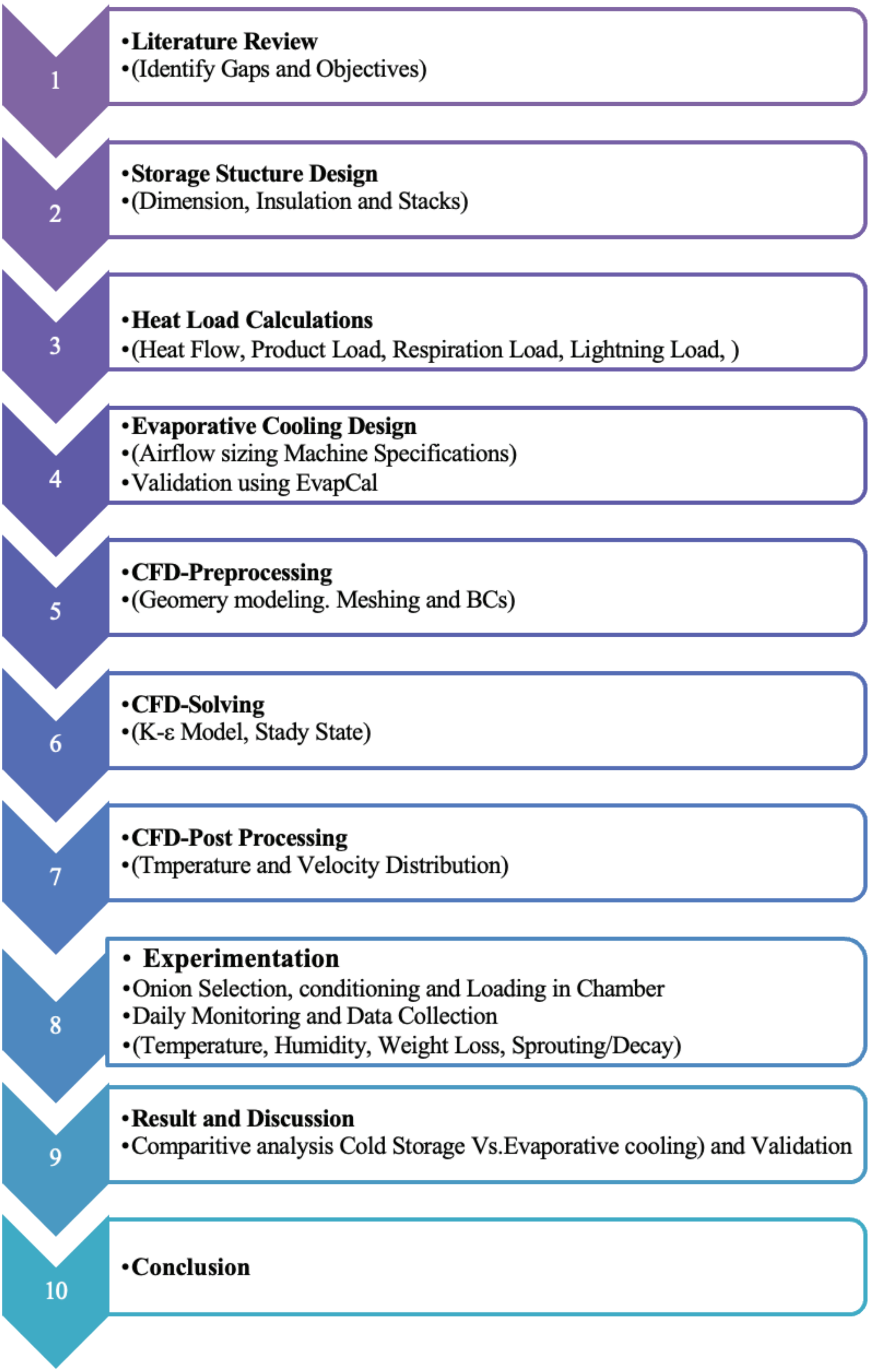

Figure 1. Experimental methodology.

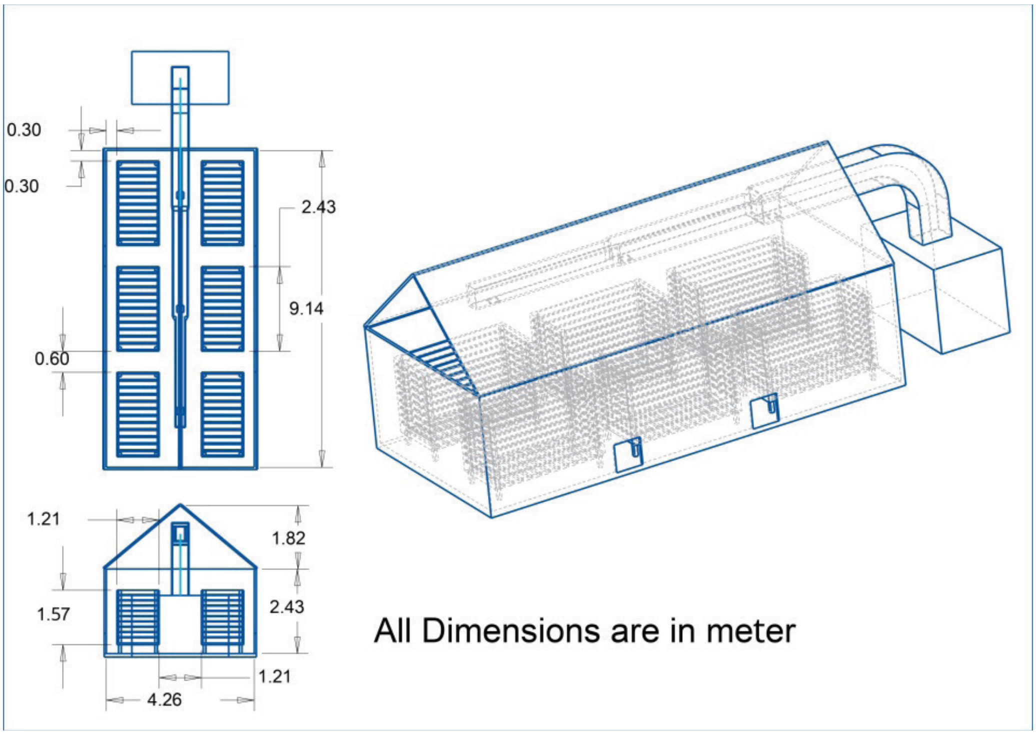

Figure 2. Storage structure layout.

the structure and respiration as the latent heat is continually drained in this one pass airflow system. The objective here is to determine the required airflow capacity (measured in cubic meters per minute, CMM) and select an appropriately sized indirect-direct evaporative cooler.

a) Conventional Cold Storage

The entire heat load was computed for structure operated at 26 °C and 70% RH. The heat load calculation is accomplished using equations1-11. Equation 1 and 2 used to calculate surface area and volume of cold storage occupied by onion. Equation 3 and 4 used to calculate size of wooden stack and number odf wooden stack. The volume of cold storage has been determined as follows:

Surface Area calculation

Wall area:

$$A_{Wall} = 2 \times (L \times H) + 2 \times (W \times H)$$
$$= 2 \times (9.144 \times 2.43) + 2 \times (4.26 \times 2.43)$$
$$A_{Wall} = 2 \times = 65.12\ m^2$$

Roof Area:

$$A_{Roof} = L \times W = 9.144 \times 4.26 = 38.94\ m^2$$

Floor Area:

$$A_{Floor} = L \times W = 9.144 \times 4.26 = 38.94\ m^2 \tag{1}$$

$$\text{Total Volume of storage sructure} = \frac{\text{Weight of onion}}{\text{Onion density}} \tag{2}$$

$$\text{Internal dimension of wooden stack} = \text{l x b x h} \tag{3}$$

$$\text{No. of wooden stack} = \frac{\text{onion Weight}}{\text{Weight of onion in each stack}} \tag{4}$$

The overall heat transfer coefficient

Outside heat transfer coefficient (h_o) is 15 W/m²·K, inside heat transfer coefficient (h_i) is 10 W/m²·K, Thermal conductivity of PUF (k_1) is 0.028 W/m·K, and Thickness PU wall 0.06 m (wall), 0.05 m (roof), 0.1 m (floor). Equation 5 is used to calculate heat transfer coefficient considering inside and outside heat transfer coeffient.

$$h = \frac{1.163}{\frac{1}{h_o} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \cdots + \frac{1}{h_i}} \tag{5}$$

Heat Gain Through Walls, Roof, Floor

Assuming steady state heat flow and external temp 40°C, internal 26°C, ΔT = 14 K. The heat flow is calculated by equation 6.

$$Q = hA(T_{out} - T_{in}) \tag{6}$$

Wall

$Q_{Wall} = 0.503 \times 65.12 \times 14 = 458.3\ W = 0.458 kW$

Roof

$Q_{Roof} = 0.56 \times 38.94 \times 14 = 305.5\ W = 0.306 kW$

Floor

$$Q_{Floor} = 0.36 \times 38.94 \times 14 = 196.1\ W = 0.196kW$$

Product Load

Total onion inside storage is 25000kg. Assume onions harvested at ambient 35°C, storage at 26°C, so ΔT = 9 K.

Cooling load required from the product exchange calculated by equation 7.

$$\text{Product Load } (Q_p) = \frac{m\, C_p (T_{enter} - T_{store})}{3600}$$
$$\text{Product Load } (Q_p) = \frac{25000 \times 3.34 \times 9}{3600} = 208.75\ kW \quad (7)$$

Product Respiration Load

Assumed respiration rate of onion as 1.9 kJ/kg, product perspiration calculated by equation 8.

$$\text{Product respiration } (Q_R) = \frac{\text{m x Respiration rate}}{3600}$$
$$\text{Product respiration } (Q_R) = \frac{25000 \times 1.9}{3600} = 13.19\ kW \quad (8)$$

Lightning Load

Assuming n=5 lights, each of 40 W and operating 10 hours/day, the lightning load calculated by equation 9.

$$\text{Lightning Load } (Q_L) = \frac{n \times t \times p}{1000}$$
$$\text{Lightning Load } (Q_L) = \frac{5 \times 10 \times 40}{1000} = 2\ \text{kWh/day} \quad (9)$$

Total Cooling Load

Total cooling load is algebraic summation of heat gain from wall, roof floor, respiration load and lightning load. Total heat load is calculated equation 10.

$$\text{Total Cooling Load } (Q_T) = Q_{Wall} + Q_{Roof} + Q_{Floor} + Q_R + Q_L$$
$$\text{Total Cooling Load } (Q_T) = 0.458 + 0.306 + 0.196 + 13.19 + 0.2 = 14.35\ kW \quad (10)$$

Tonn of refrigeration

Tonn of refrigeration provides a simple, relatable figure to compare the effectiveness and size of different cooling units, helping in the selection of the right equipment. Equation 11 gives TR value.

$$\text{TR} = \frac{14.35}{3.517} = 4.08\ \text{TR} \quad (11)$$

The thermal load based steady state cooling load for the storage structure is the sum of heat loss through the walls, roof and floor (1.11 kW), respiration heat load from 25 tons of onions (13.19 kW) and lighting load (0.2 kW) and is approximately 14.5 kW or 4.1 TR (1 TR = 3.517 kW). Additionally, an initial pull-down product load of approximately 17.4 kW is required to reduce the product temperature from ambient (35°C) to storage conditions (26°C), particularly during the first 12 hours of storage operation. To ensure continuous operation under varying ambient conditions, system cycling, compressor efficiency factors, and to accommodate startup transients and peak loads, an engineering safety margin of 1.8–2.0 times the steady-state load is typically adopted in practice for agricultural cold storages. Therefore, the cumulative design load requirement is estimated at approximately 7.5–8.2 TR., The capacity of the refrigeration unit was selected as 8.5 TR which provides appropriate leeway for operating variation, load variation and to ensure optimum temperature & relative humidity regulation for the entire storage time, to further ensure reliable operation. This capacity is fully justified by the calculated loads and practical engineering design considerations for such storage structures.

b) Design of Evaporative Cooling System

The design of EC structure was carried out using the heat load method. Heat load method ensures effective temperature reduction and air distribution within the onion storage facility. The total sensible (Qs) and latent heat loads (QL) were calculated based on internal and external heat gains. The heat gain includes solar radiation through the roof and walls, infiltration, product respiration, equipment load, and lighting. Equation 12 and 13 gives sensible heat load (Qs) and latent heat loads (QL). The two-stage indirect-direct EC system was selected to optimize energy efficiency and uphold the mandatory temperature and humidity condition. V is volume of cold storage=165.941 m^3, ACH is air changes per hour= 86, specific heat of air (C_p)= 1.02 Kj/kgK, temperature difference(ΔT). Equation 14 used to compute total heat load.

$$Q_S = \frac{1.2 \times V \times ACH \times C_p \times \Delta T}{3600}$$
$$PQ_S = \frac{1.2 \times 165.94 \times 86 \times 1.02 \times 13.4}{3600} = 6.49kW$$
$$= 22{,}161 BTU/hr \quad (12)$$
$$Q_L = \frac{1.2 \times V \times ACH \times W_{diff} \times L_V}{3600}$$

$$Q_L = \frac{1.2 \times V \times ACH \times W_{diff} \times L_V}{3600}$$
$$Q_L = \frac{1.2 \times 165.94 \times 86 \times 0.07 \times 2450}{3600} = 0.4kW =$$
$$Q_{Total} = Q_S + Q_L \quad (14)$$
$$Q_{Total} = 6.49 + 0.4 = 6.84\ \text{kW} = 23{,}328\ \text{BTU/hr}$$

The calculated total sensible heat load was 22,161 BTU/hr (6.49 kW), and the total heat load reached 23,328 BTU/hr (6.84 kW). The aim has an interior temperature of 26–27 °C and 70% RH; the supply air temperature is about 23 °C. The required air circulation demand computed using following equation.

$$\text{CMM} = \frac{\text{RSH}}{1.944 \times \Delta T}$$

$$\text{CMM} = \frac{6.84}{1.944 \times \Delta T \times 3.5} = 84.96 \qquad (15)$$

The air flow demand is at 84.96 CMM. The system used a high efficiency indirect-direct evaporative cooler consuming 2.1 kW of power that greatly lowered the operational energy demand. The CFD simulations were carried out to verify the air velocity, the uniform temperature distribution and the thermal comfort in the entire storage area. In this study, design calculations and CFD results for the evaporative cooling structure were validated using EvapCal software. EvapCal software is developed by ISHRAE. It is dedicated estimate of reliable cooling loads, airflow rates and energy performance of evaporative cooling systems based on climatic conditions and building factors. The analysis was carried out using EvapCal, using the following boundary conditions: exterior dry bulb temperature 40.4 °C, wet bulb temperature 25.9 °C, goal room temperature 27 °C, relative humidity 70%, and two-stage indirect-direct evaporative cooling strategy. The EvapCal software computed sensible heat load and total heat load of 22,161 BTU/hr of 23,328 BTU/hr respectively. The required airflow rate was 84.95 CMM with 86 air changes per hour (ACH). The cooling capacity was estimated as 8.5 TR while maximum power consumption was 2.1kW. Additionally, EvapCal showed 82% reduction in the peak power demand compared to the results of traditional cold storage which were in accordance with the manual and CFD-based results. The EvapCal software used validate the system performance under varied climatic conditions.

CFD Analysis

The Computational Fluid Dynamics (CFD) was adopted to provide to investigate temperature gradient, airflow distribution, and humidity patterns within the onion storage structure. These parameters are difficult to capture by experimental results. CFD allows virtually optimized critical design elements such as air intake layout, diffuser placement and airflow rates. It saves time and cost in iterative physical prototyping. The CFD study in this work was accomplished by using ANSYS Fluent 2021 R1. There are three stages of CFD analysis. The analysis starts from design and meshing of the geometry. The next stage is solution for thermodynamic parameters and end with post-processing to visualize the airflow and heat fields.

Geometric modelling

Figure 2 depicts three-dimensional geometry of the indirect-direct evaporative cooling structure was developed using SolidWorks 2023. The model accurately represents louvers, air duct, storage racks and dimensions of cooling chamber. The geometry was constructed to reflect the actual experimental setup, ensuring realistic simulation of airflow and thermal characteristics. The CAD model was then exported in STEP format. Same step file imported into ANSYS Space Claim for minor adjustments and preparation for computational analysis. The finalized geometry was subsequently used in ANSYS Fluent to perform detailed Computational Fluid Dynamics (CFD) simulations.

Meshing

Meshing is also called as discretization. Discretization of the geometry is performed using ANSYS ICEM 2021 module. Figure 3 shows meshed geometry. The hexahedral elements are preferred for meshing. Hexahedral elements are especially used in the structured grid systems. The hexahedral elements show better alignment with the principal flow direction. Hexahedral element accurately captures the velocity changes along the length and boundary layer formation. These elements provide better numerical stability and computing efficiency than unstructured meshes. Structured meshing techniques produce a uniform and ordered grid. Hexahedral element produce structured meshes as seen in the figure. This hierarchical structure tolerates to effectual mesh refinement near wall boundary layers and geometric obstacles to improve overall solution accuracy [48]. The unconventionality of the mesh was confirmed to ensure that the results are independent of mesh size. Various meshing arrangements were tested from rough to fine grids to study the effect of mesh density on the key performance indicators [48].

A comprehensive mesh unconventionality assessment was steered to confirm the accuracy of the simulation results with computational efficiency. Based on test results

Table 2. Mesh independence test results

Meshing Type	No. of Elements	Avg. Temperature(°C)	Observations
Coarse	2,50,000	26.15	Course mesh, fast simulation but less precise.
Medium	5,00,000	26.1	Fine mesh, Improved results near intricate portion.
Fine	10,00,000	26.08	Mesh refinement, insignificant alteration in temperature.
Very Fine	18,00,000	26.06	No significant improvement, computational cost increases.

final mesh size selected for the cold room simulation. Table 2 summarizes mesh independence test parameters. The grid was gradually refined from course size. The air diffusers, shelf interior/exteriors, and doors are considered as critical regions. These locations are expected to be more pronounced for flow separation and temperature gradients are [48]. The temperature values at these points were used for the study of mesh quality and solution convergence. The difference in average temperature between the fine and refined mesh was less than 0.1 °C, indicating that additional refinement had minimal influence on the results [48]. Therefore, a mesh containing nearly 1,000,000 elements was selected as an optimum balance between numerical accuracy and computational time. This mesh provided stable prediction of airflow and thermal behaviour inside the storage chamber without excessive computational requirements [48]. Figure 3 illustrates the computational mesh generated for the storage structure. Further mesh refinement produced only negligible changes in the simulation results, confirming grid independence. The adopted mesh configuration provided sufficient resolution for capturing the important thermal and airflow characteristics within the computational domain [48]. The structured grid around critical region provides sufficient resolution in terms of temperature and flow behaviour [48].

Boundary condition

Boundary condition is essential to solve governing equation in computational domain. The ambient conditions for the CFD analysis were an inlet air DBT of 40.3 °C, WBT of 25 °C. The inlet air flow rate was maintained at 84.95 cubic meter per minute. A 4-way air diffuser of size 600 mm × 600 mm was used for air supply in both the cold storage and evaporative cooling structures. Each diffuser supplied air at 26 °C with a flow rate of 28.31 CMM. Three diffusers were installed at the top side of each storage structure. Low-level return risers of size 550 mm × 450 mm were provided at the bottom side as outlet boundaries. Each riser handled an air flow rate of 16.99 CMM, and five risers were used in total. The applied heat flux values were 17.22 W/m² for the north wall, 28 W/m² for the south wall, 37.43 W/m² for the east wall, and 32.34 W/m² for the west wall. Adiabatic thermal conditions were assigned to the end walls. The CFD boundary conditions are presented in Table 4.

Computational analysis

In this study, a steady state model of incompressible airflow is developed to simulate the actual storage conditions inside an onion storage chamber. The model has been used to study the airflow behaviour, ventilation characteristics and heat transfer within the storage space. The onion bulk has been treated as a porous medium with specified thermal properties to represent the resistance to airflow and heat exchange. The volumetric heat source of respiration heat generated by onions was considered in the simulation. The heat generation values ranged from 2 to 10 W/m^3 depending on the onion type and storage conditions [27]. A second order upwind discretization scheme was used to improve accuracy of the numerical solution and decrease the errors of interpolation, which improved the stability and convergence of the solution. The standard k–ε turbulence model was applied to predict turbulent airflow and energy dissipation inside the storage structure. The model was able to predict the airflow distribution and the temperature variation in the storage chamber well. Convective heat transfer between the onion surface and surrounding air

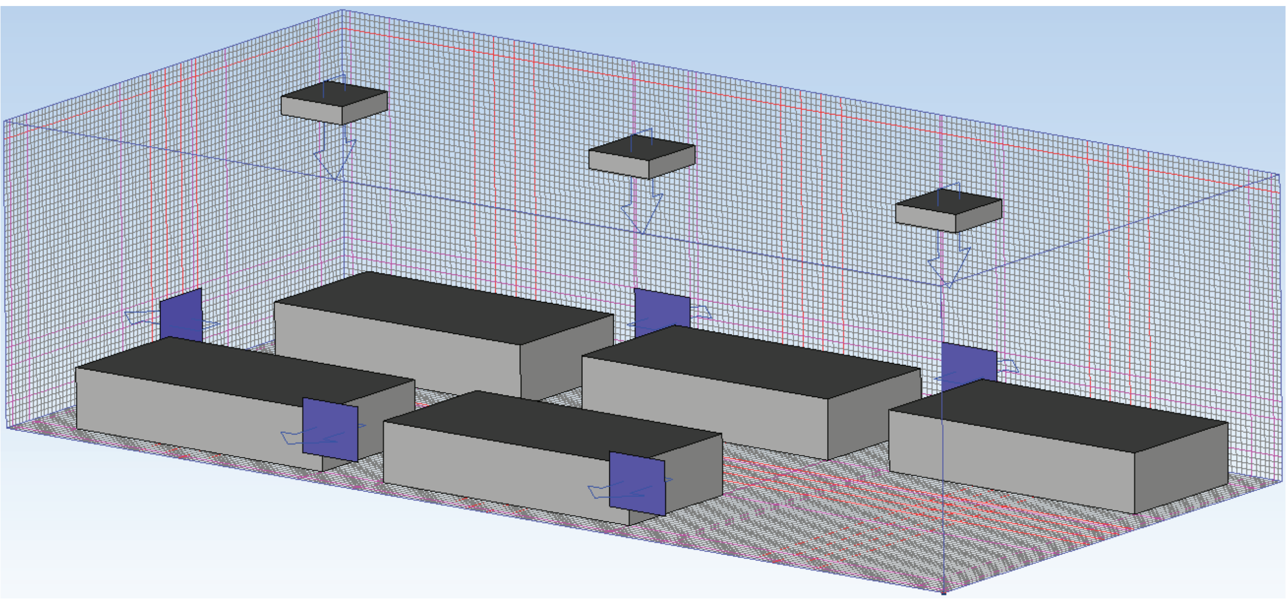

Figure 3. Storage structure meshing.

Table 3. Boundary condition

Parameter	CFD Simulation
Ambient dry bulb temperature	40.3 °C
Ambient wet bulb temperature	25 °C
Indoor air temperature	26 °C
Indoor relative humidity	70%
Cooling arrangement	Air supplied through diffusers with return risers
Air velocity in occupied zone	0.2–0.5 m/s
Total inlet air flow rate	84.95 CMM
Air flow rate through each diffuser	28.31 CMM (three diffusers installed in each structure)
Supply air temperature	26 °C
Return air flow through each riser	16.99 CMM (five risers provided in each structure)
Dimensions of return riser	550 mm × 450 mm
walls Thermal boundary condition	Individual wall heat flux values applied
Heat flux at north wall	17.22 W/m²
Heat flux at south wall	28 W/m²
Heat flux at east wall	37.43 W/m²
Heat flux at west wall	32.34 W/m²
Boundary condition at end walls	Adiabatic condition applied

was also considered to obtain realistic thermal behaviour. In addition, latent heat released due to moisture evaporation during onion respiration was incorporated into the analysis. Suitable boundary conditions were imposed for all simulations. The energy equation was coupled with the heat evolved from onions and the airflow pattern was modified to effectively evacuate the heat from the storage space. The developed CFD model was able to accurately predict the heat accumulation and dissipation inside the chamber. The computational study also provided detailed information regarding airflow distribution, heat transfer characteristics and evaporative cooling performance, which are important in improving the post-harvest storage efficiency and reducing the spoilage of onions.

EXPERIMENTATION

Experimental Setup

In this study, two types of storage systems were designed and implemented within identical thermally insulated storage structures to enable a direct performance comparison: (i) a conventional vapor compression-based cold storage system, and (ii) an advanced two-stage indirect-direct evaporative cooling system.

A conventional cold storage system was fitted with 8.5 ton Daikin vapour compression refrigeration unit and worked at a target room temperature of 26 ± 0.5 °C with 70 ± 2% relative humidity. The room was fitted with three 4-way diffusers (600 mm x 600 mm) at ceiling level that disseminated air to achieve uniform cooling within the chamber. Five low level return air risers (550 mm x 450 mm) were provided at floor level for effective recirculation of air and to ensure homogeneity of temperature. In contrast, the evaporative cooling system used a high-performance HMX IDECool 6 two-stage indirect-direct evaporative cooling unit. The system was designed to furnish air at 23 °C in a room maintained at a steady state of roughly 26.5 ± 0.5 °C with relative humidity values of 68–70%. The evaporative cooling unit was operated at the airflow rate of 84.95 CMM and maximum power consumption of 2.1 kW. It was developed to work in a single-pass ventilation system with 100 percent fresh air for effective removal of latent heat and moisture and improvement of indoor air quality. Importantly, the internal arrangement of the wooden stacking units and the loading patterns of the product were the same for both storage systems, so that any changes in performance could be traced only to the technique of cooling.

Experimental Procedure

A study was conducted experimentally to assess and compare the efficiency of two post-harvest storage systems viz. Conventional Cold Storage and an Evaporative Cooling-based Storage System for onion preservation for a duration of 30 days. The experimental system was designed for operation under regulated realistic settings. Well-cured and freshly harvested onions (Panchganga variety) were obtained from a local commercial farm in [Sambhajinagar, India] at 85–90 days maturity. The onions were conditioned initially at ambient temperature for 24 hours before being placed in the storage chambers. Each storage system was charged with a similar quantity of onions (25 metric

Table 4. Experimental results: Conventional cold storage

Day	Room Temp (°C)	Room RH (%)	Onion Core Temp (°C)	Cumulative Weight Loss (%)	Sprouting (%)	Decay (%)	Power Consumed (kWh/day)
1	26	70	27.5	0.1	0	0	38
2	26	70	27.2	0.25	0	0	38
3	26	71	27.1	0.45	0	0	38
4	26	71	27	0.65	1	0	38
5	26	71	27	0.9	1	0	38
6	26	70	26.9	1.1	2	0	38
7	26	70	26.8	1.3	2	1	38
8	26	70	26.8	1.55	3	1	38
9	26	70	26.8	1.8	3	1	38
10	26	70	26.7	2.1	4	1	38
11	26	70	26.7	2.4	5	2	38
12	26	71	26.6	2.7	5	2	38
13	26	71	26.6	3	6	2	38
14	26	70	26.5	3.25	6	2	38
15	26	70	26.5	3.5	7	3	38
16	26	70	26.5	3.8	7	3	38
17	26	70	26.4	4.1	8	3	38
18	26	70	26.4	4.4	8	4	38
19	26	70	26.4	4.75	9	4	38
20	26	70	26.3	5.1	10	4	38
21	26	70	26.3	5.45	10	5	38
22	26	70	26.3	5.8	11	5	38
23	26	70	26.2	6.1	11	5	38
24	26	70	26.2	6.45	12	6	38
25	26	70	26.2	6.8	13	6	38
26	26	70	26.2	7.1	13	7	38
27	26	70	26.1	7.4	14	7	38
28	26	70	26.1	7.7	14	8	38
29	26	70	26.1	8	15	8	38
30	26	70	26.1	8.3	15	9	38

tonnes) evenly split among wooden stacking units, each with dimensions of 1.21 m × 2.43 m × 1.52 m, and with sufficient airflow clearance between and around stacks.

The experiment was carried out continuously for 30 days under controlled field circumstances. Throughout this period, a full suite of physical parameters was recorded at regular intervals. Ambient outdoor conditions comprising dry bulb temperature and wet bulb temperature were taken at three times daily (08:00, 12:00 and 16:00 hours). Internal storage chamber temperature and relative humidity were continually monitored using calibrated digital temperature-humidity data loggers (accuracy: ±0.5 °C for temperature and ±2% RH). In addition, the core temperature of randomly selected onions was monitored on a daily basis using fine gauge thermocouples inserted at the geometric center of bulbs. The weight loss was determined by weighing a selected sample lot of onions daily (beginning weight accurately recorded) using an electronic precision scale (accuracy ±0.01 g). The onions were visually inspected for sprouting and microbiological decay every three days and expressed as a percentage of the total onions sampled. The electrical energy consumption of each system was measured by dedicated Class-1 accuracy energy meters and the airflow rates were verified by comparing with EvapCAL software created by ISHRAE. Also, heat load and cooling capacity were determined as per ASHRAE standards and airflow characteristics and thermal distribution were further assessed with Computational Fluid Dynamics (CFD) simulations performed in ANSYS Fluent. All the experiments were done in triplicates to ensure repeatability and

Table 5. Experimental results: Evaporative cooling

Day	Room Temp (°C)	Room RH (%)	Onion Core Temp (°C)	Cumulative Weight Loss (%)	Sprouting (%)	Decay (%)	Power Consumed (kWh/day)
1	26.5	68	26.8	0.08	0	0	14
2	26.5	68	26.5	0.18	0	0	14
3	26.5	68	26.4	0.28	0	0	14
4	26.5	69	26.3	0.38	0	0	14
5	26.5	69	26.3	0.5	0	0	14
6	26.5	68	26.2	0.65	0	0	14
7	26.5	68	26.1	0.8	0	0	14
8	26.5	68	26.1	0.95	0	0	14
9	26.5	68	26	1.1	0	0	14
10	26.5	68	26	1.3	0	0	14
11	26.5	68	25.9	1.5	0	0	14
12	26.5	68	25.9	1.7	0	0	14
13	26.5	68	25.9	1.9	0	0	14
14	26.5	68	25.8	2.1	0	0	14
15	26.5	68	25.8	2.3	0	0	14
16	26.5	68	25.8	2.55	0	0	14
17	26.5	68	25.7	2.8	0	0	14
18	26.5	68	25.7	3.05	0	0	14
19	26.5	68	25.7	3.3	0	0	14
20	26.5	68	25.6	3.55	0	0	14
21	26.5	68	25.6	3.8	0	0	14
22	26.5	68	25.6	4.05	0	0	14
23	26.5	68	25.6	4.3	0	0	14
24	26.5	68	25.5	4.55	0	0	14
25	26.5	68	25.5	4.8	0	0	14
26	26.5	68	25.5	5.05	0	0	14
27	26.5	68	25.5	5.3	0	0	14
28	26.5	68	25.5	5.55	0	0	14
29	26.5	68	25.5	5.8	0	0	14
30	26.5	68	25.5	6	0	0	14

to minimise the effect of experimental variability. Statistical analysis of the recorded data was performed to compare the performance of the two systems and to quantify their effects on storage temperature uniformity, onion quality preservation and energy efficiency. The experimental results of conventional cold storage and evaporative cooling system are separately given in Table 4 and 5.

COMPUTATIONAL RESULTS

Cold Storage

The CFD simulation for the conventional cold storage system was performed at a storage temperature of 26 °C. Figure 4 presents the temperature contours and airflow distribution inside the storage chamber. The colour scale represents the temperature change, where blue areas correspond to lower temperatures. The flow streamlines illustrate the transport of the cold air into the storage area. The storage racks affect the flow path and produce local cooling regions. The air is supplied from the diffusers and flows towards the central region, which leads to a more uniform temperature distribution in the chamber. The predicted temperature field confirms the effective cooling performance with only few localized hot spots inside the storage room.

Figure 5 illustrates the temperature profile and airflow pattern along the vertical centre plane of the storage system using evaporative cooling. The dominance of blue shades in the vicinity of the cooling inlets indicates effective cooling

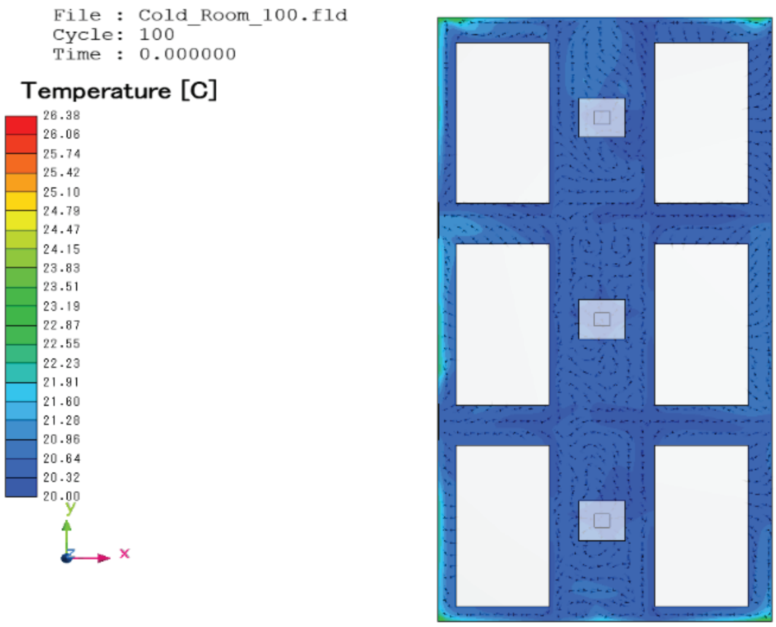

Figure 4. Temperature and air movement inside conventional cold storage.

performance; marginally higher temperatures are observed near the walls and upper parts of the structure. The airflow streamlines show that the cool air supplied through the ceiling diffusers is evenly distributed over the storage chamber. The circulation pattern is instrumental in minimizing temperature gradients within the storage space. The simulation results validate that the evaporative cooling system can maintain relatively uniform thermal conditions throughout the onion storage structure.

Figure 6 illustrates the temperature distribution and airflow pattern in the vicinity of the diffuser section of the conventional cold storage system. The figure indicates that the cooled air supplied through the diffusers enters the storage chamber and spreads over the available space. While circulating, the cold air gets mixed with the relatively warmer air present inside the chamber. The airflow moves downward near the diffuser outlets and then spreads across the storage area leading to better air circulation inside the chamber. The results demonstrate that proper diffuser positioning plays an important role in achieving uniform cooling and maintaining the required storage conditions inside the cold storage system.

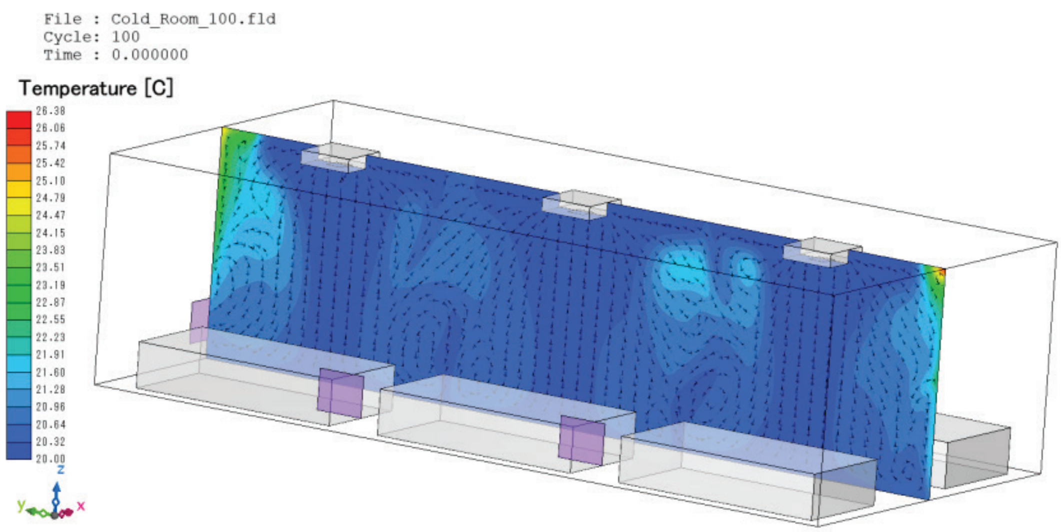

Figure 5. Temperature and air movement inside conventional cold storage at vertical middle plane.

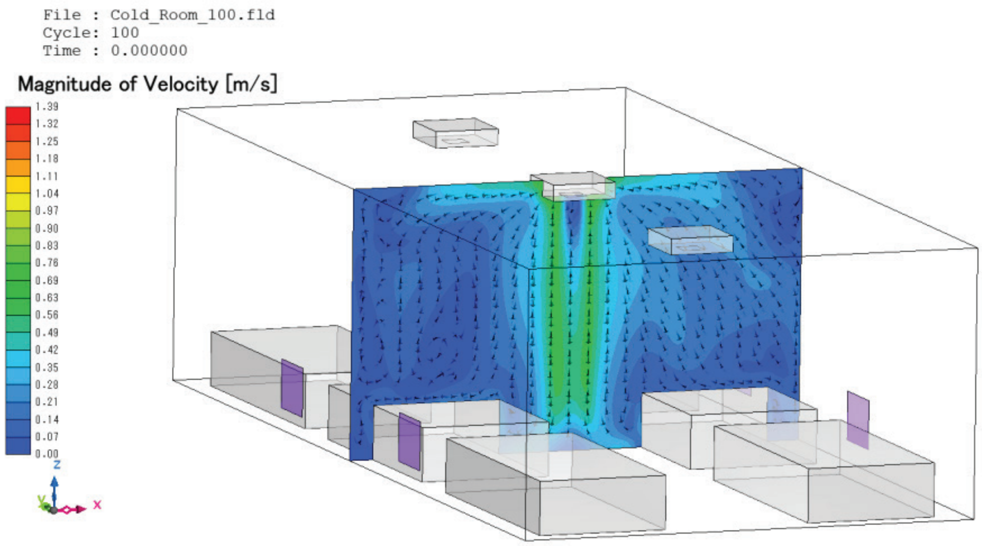

Figure 6. Temperature and air movement inside conventional cold storage diffuser plane.

Evaporative Cooled Structure

The CFD analysis for the evaporative cooling storage structure was performed at an operating temperature of 27 °C. Figure 7 presents the airflow and temperature distribution at the floor level and compares it with the conventional cold storage system operating at 27 °C. The temperature contours indicate that the evaporative cooling system maintained lower temperature zones throughout most of the storage region. However, in some locations, the temperature was slightly higher and which could be attributed to comparatively less air circulation. The air flow pattern also indicates non-uniform cooling near some storage rack regions which might result in localized temperature variations inside the storage chamber.

Figure 8 shows the temperature distribution along the vertical direction and the motion of air inside the standard cold storage system. The temperature gradient is more extreme than in the evaporative-cooled system with

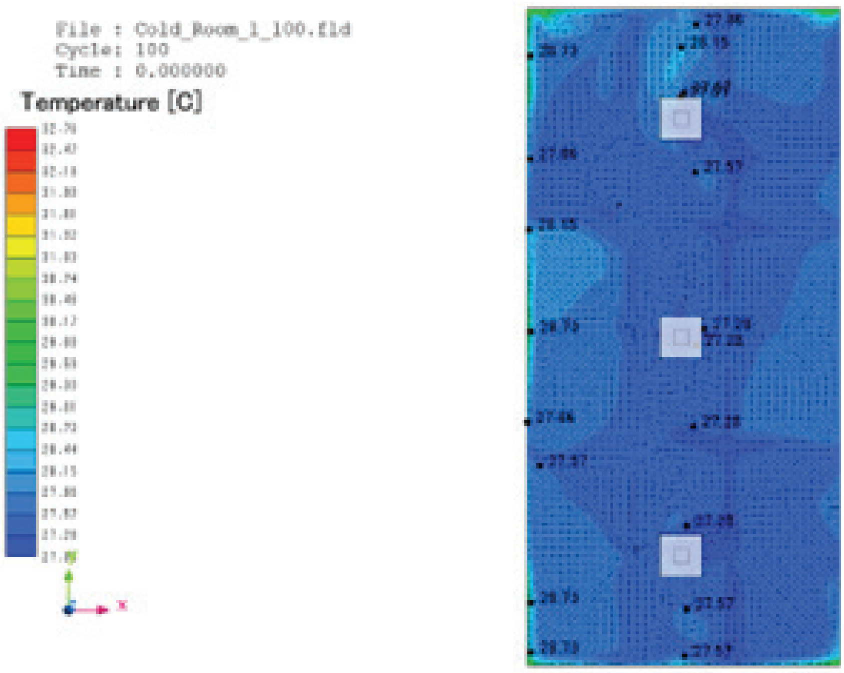

Figure 7. Temperature and air movement inside evaporative cooled storage floor level.

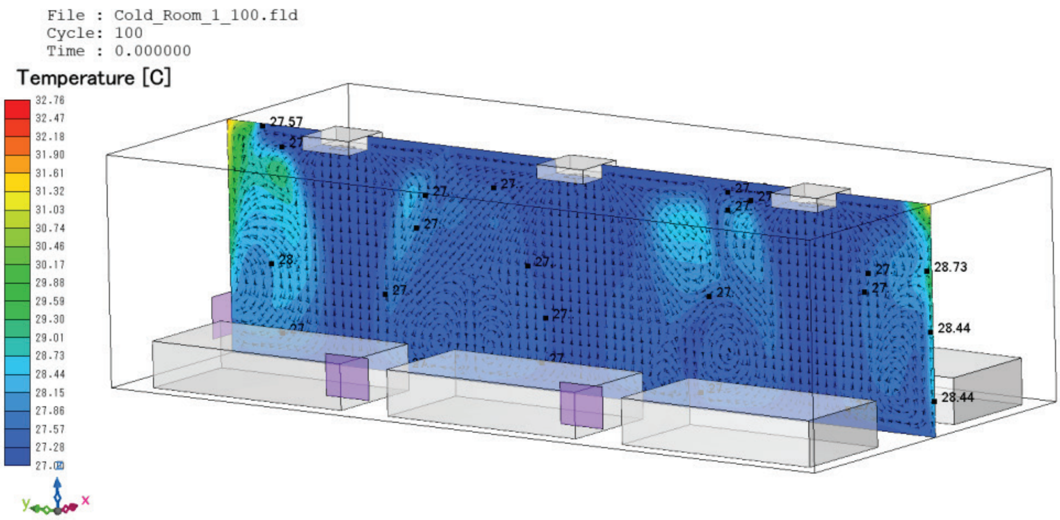

Figure 8. Temperature and air movement inside EC storage vertical middle plane.

warmer zones near the walls and ceiling. The air circulation is not as even, and there are clear warm spots where there is less air movement. This implies that the evaporative cooled system is more efficient in attaining uniform temperature distribution than the typical cold storages cooling system. Perishable products may be stored under unstable conditions due to temperature changes.

Proper air flow and a continuous supply of fresh air are important in maintaining post-harvest quality of onions in storage. Good air circulation controls interior temperature and relative humidity avoiding the creation of localised hot patches and helps the elimination of ethylene and other spoiling gases. Evaporative cooling systems also use 100% fresh air once through as opposed to recirculated air in conventional cold storage. This improves the storage environment by continuously removing heat and moisture generated by product respiration. This airflow method decreases the possibility of microbial development, sprouting and physiological deterioration. The present study shows the effectiveness of the system in keeping constant heat and humidity profiles by the optimised air distribution obtained by CFD-guided diffuser placement and validated by experimental data. Thus, the evaporative cooling system provided better storage conditions and significant reduction in spoiling than the typical refrigerated storage.

Figure 9 demonstrates conventional cold storage system temperature distribution and airflow pattern around the storage stacks and walls. The temperature variations are

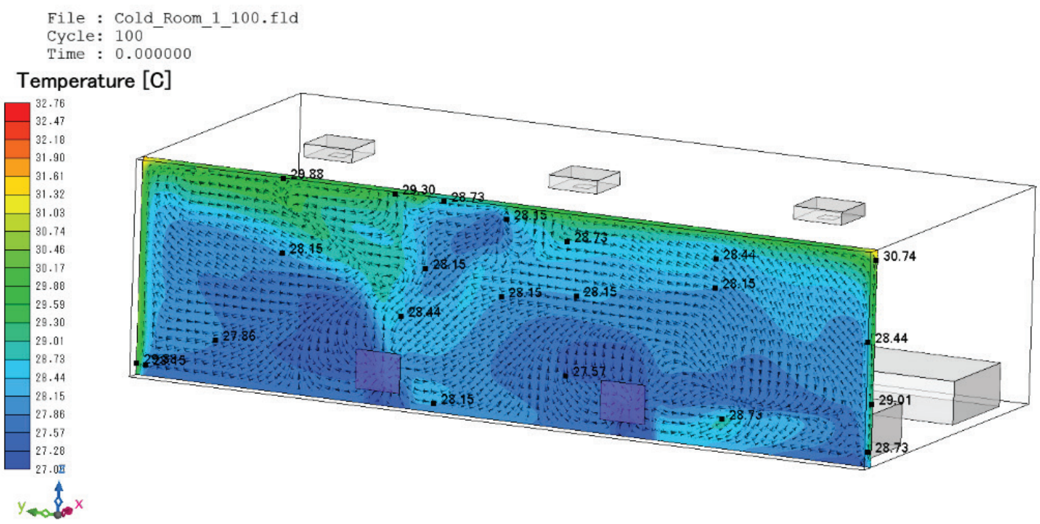

Figure 9. Temperature and air movement inside EC storage near wall.

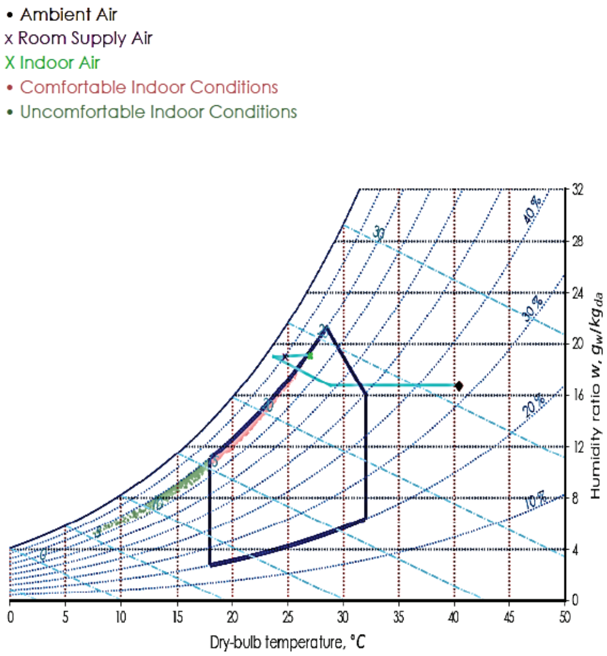

Figure 10. Psychrometric analysis in evaporative cooling at 27˚C.

especially significant near the walls where air movement is very slow. The flow streamlines of the airflow indicate a reduced flow in some areas leading to temperature stratification. The regions close to the storage stacks showed slightly higher temperatures indicating poor distribution of cooling effect. This demonstrates the risk of damage the quality and shelf life of the stored items because of non-uniform cooling in standard cold storage.

Figure 4-9. Comparison of temperature distribution of evaporative cooled cold storage system and conventional cold storage system Figure 4-9 shows that the evaporative cooled cold storage system has a better temperature distribution than the conventional cold storage system. The evaporative cooled cold storage system has flow patterns which enhance the mixing of the cooled air thereby reducing the temperature gradient and ensuring a uniform storage condition. The conventional cold storage system has temperature variation especially at the walls and in storage racks thus indicating a poor cooling distribution. Such a comparative analysis shows the advantages of an evaporative cooling system in improving the thermal performance and energy efficiency of cold storage applications.

The comfort analysis of the evaporative cooling system at 27 °C depicted in figure 10. It gives information about thermodynamic behaviour of air when cooled and humidified. The chart shows indicate ambient air, room stream air, indoor air, and stages of air treatment. The blue region enclosed shows the range of air temperatures generated by the cooling system, which maintains the air within the comfortable indoor conditions (shown by the green area) and avoids the uncomfortable zone in pink. The psychrometric research shows that the evaporative cooling system is able to keep the indoor air conditions within the comfort zone and achieve significant energy efficiency benefits compared to conventional refrigeration based cold storage.

Assessment of Spoilage, Weight Loss and Decay

The appropriate storage conditions are used to avoid fungal development, weight loss and deterioration. Controlled temperature and relative humidity (RH) within the storage structure are considered are effective storage condition. Data from the present study showed that the evaporative cooling system was able to maintain a constant storage temperature of 26.5°C with 68% RH. Meanwhile, the conventional cold storage maintained similar temperatures (26°C) and RH (70%) due to practical restrictions in the field. The comparison of weight loss, sprouting and decay over the 30-day storage period clearly shows the advantages of evaporative cooling. Onions stored under evaporative cooling showed decreased cumulative weight loss (6% vs 8.3%) and interestingly over the duration neither sprouting or fungal rot was noted. Whereas, onions under traditional cold storage exhibited a continuous sprouting (up to 15%) and decay (up to 9%) to the 30th day. This is due to greater air circulation (increased ACPH), a more uniform RH, and elimination of localized condensation patches, which are frequent drivers of fungal outbreaks in cold storage systems. In addition, the evaporative system was able to maintain a constant moderate RH (68%) that prevented both extreme dehydration and conditions conducive to fungus development a common problem when RH is >75% or variable. Stable onion core temperatures in evaporative cooling (~25.5 °C) similarly favoured metabolic balance, reducing respiration rates without stimulating sprouting, as in the cold storage where oscillations caused stress reactions. In terms of energy consumption, evaporative cooling used substantially lower power (14 kWh/day against 38 kWh/day) and hence is a cost effective alternative for small and marginal farmers while giving better overall storage results. Thus, evaporative cooling under Indian climatic conditions provides not only the optimum temperature and humidity for onion storage but also reduces the weight loss, sprouting and fungal spoilage significantly as compared to conventional cold storage with far lower operational energy and cost.

Comparative Analysis and Validation

The performance of conventional cold storage and evaporative cooling systems for preservation of onions was evaluated by comparing the results of manual heat load calculations, CFD simulations, EvapCal software and experiments in detail. Manual computations produced first-order estimates of the cooling requirements, air flow rates and energy consumption based on thermodynamic principles. The CFD simulation provided spatially resolved

Table 6. Comparison of performance parameters (manual, CFD, and experimental results)

Parameter	Conventional Cold Storage			Evaporative Cooling		
	Manual Calculation	CFD Results	Experimental Result	Manual Calculation	CFD Results	Experimental Result
Cooling Load (kW)	14.35 kW	14.5 kW	Confirmed (14.5 kW)	6.84 kW	6.5 kW	Confirmed (6.8 kW)
TR (Tons of Refrigeration)	4.08 TR (design: 8.5 TR)	8.5 TR	8.5 TR	N/A	N/A	N/A
Supply Airflow (CMM)	Estimated	86 CMM	86 CMM	84.95 CMM	85–86 CMM	85 CMM
Room Air Temperature (°C)	26	26	26	26.5	26.5	26.5
Relative Humidity (%)	70%	70%	70%	68%	68%	68%
Power Consumption (kWh/day)	Estimated 35–38	35–38	38	14	14	14
Weight Loss after 30 days (%)	Theoretical	8%	8.30%	6%	6%	6%
Sprouting after 30 days (%)	NA	15%	15%	0%	0%	0%
Decay after 30 days (%)	NA	9%	9%	0%	0%	0%
Energy Savings Compared to Cold Storage	NA	N/A	N/A	82–86%	82–86%	86%

information on the airflow distribution, temperature gradient and humidity control, which were also confirmed by 30-day practical trials. The overall cooling load for the traditional cold storage structure at 26 °C and 70% relative humidity was calculated manually to be around 14.35 kW (4.08 TR), but it is recommended by realistic design guidelines to select an 8.5 TR refrigeration system to take care of transient and peak loads. Conversely, the indirect-direct evaporative cooling structure design provided a total heat load of 6.84 kW and an air flow rate of 84.95 CMM, indicating the much-reduced cooling demand of the evaporative method.

The results were also verified using CFD analysis with a detailed spatial resolution of temperature profiles and airflow patterns. In operation of evaporative cooling, CFD revealed homogeneous dispersion of air with minimum temperature gradients (room temperatures ~26.5–27 °C) whereas the conventional system showed more severe stratification and uneven cooling. The regularity of the airflow and the temperature gradient anticipated by our CFD analysis are in agreement with the results reported by Serap et al.[43] for cold storage and by Vala et al. [44] for evaporative systems, thereby confirming the efficiency of the optimisation based on the CFD approach for the storage design.

These numerical results were confirmed by experimental testing during a 30-day storage period. The evaporative cooling system maintained lower onion core temperatures (25.5–26.0 °C), reduced cumulative weight loss (6.0% vs. 8.3%) and eradicated sprouting and decay, compared to the conventional cold storage which showed 15% sprouting and 9% decay after 30 days. The reduction in onion rotting (15%) found compares favourably with ventilated storage systems reported by Lawande et al. [12] and Tripathi et al. [27], showing the extra benefits of regulated airflow in EC systems. Additionally, the energy consumption of the evaporative system was 14 kWh/day compared with 38 kWh/day for cold storage, a reduction of 76.14% as opposed to the 82% save projected by EvapCal. The energy consumption decrease obtained is in agreement with the findings of Lv et al. [34] who reported 80% reduction with EC and Sipho et al.[33], showed 75% energy savings with the use of indirect cooling system + EC system. Table 6 presents the comparison of performance parameters of conventional cold storage and evaporative cooling system (manual, CFD and experimental findings). Overall, the comparison study indicates a good agreement between the manual calculations, CFD simulations, EvapCal outputs and experimental findings. The results confirm the suitability of the proposed evaporative cooling design is energy-efficient and technically effective solution for the post-harvest onion storage. Evaporative cooled storage becomes sustainable alternative to the conventional refrigeration systems.

COST ANALYSIS

The cost of major components used in both the storage systems was estimated using prevailing market prices in India. The total cost of two-stage indirect-direct evaporative cooling system was estimated to be around ₹1,49,996 and the conventional cold storage system costed around ₹1,51,636. The estimated values exclude the construction cost of the storage chamber and ducting network because these components were identical for both systems. Although the initial investment of the two systems was comparable, a considerable difference was observed in their operating energy consumption and running cost.

Air Handling Unit Power Requirement

The conventional cold storage system employed an 8.5-ton air conditioning unit with a rated power of 9.5 kW [20]

$$Power\ for\ AHU = (CMM\ \times P_s)/(6356 \times\ \eta_m\ \times\ \eta_b)$$

$$Power\ for\ AHU = \frac{84.95 \times}{6356 \times 0.85 \times 0.8} \quad (16)$$

$$Total\ Power = Power\ for\ Air\ Condensing\ Unit + Power\ for\ AHU + Humidifier\ Power \quad (17$$

$$Total\ Power = 9.50 + 2.238 + 1$$

The power requirement of the air handling unit (AHU) was estimated using Equation (16) Taking into account airflow rate of 84.95 CMM, motor efficiency of 0.85 and blower efficiency of 0.8, the calculated power of AHU was 2.238 kW. In addition, a humidifier load of 1 kW was considered. Therefore, the total power requirement of the conventional cooling system was determined using Eq. (17).

Evaporative Cooling Energy Requirement

$$\text{Power for Evaporative Pump} = 3\ \text{HP}$$
$$= 3\ \times 0.7457\ \text{kW} = 3\ \times 0.7457\ \times 16 = 35.79\ \text{kWhr per day}$$

Cost Calculation

Energy rate in India for power consumption is considered as Rs 7.34 per kWhr. Total cost required per kWhr is calculated as

$$\text{Total Cost for Air Conditioning} = \text{Total power}\ \times \text{Cost per unit} \quad (18)$$

$$\text{Total Cost for Evaporative Cooling} = \text{Total power}\ \times \text{Cost per unit} \quad (19)$$

The specifications and cost of the components of the conventional cold storage and evaporative cooling systems are given in Table 7. The storage systems were designed for a storage volume of 165.94 m³. The cooling load analysis showed that the conventional cold storage system needs an 8.5 TR refrigeration unit to maintain the desired storage conditions. In contrast, the evaporative cooling structure required only an airflow rate of 84.95 CMM for effective operation. To ensure uniform air circulation inside the storage chamber, a circulation fan rated at 22 W with an air delivery capacity of 240 m³ was installed in the cold storage unit. In addition, four LED lamps of 20 W capacity were provided for internal lighting. The total energy consumption of both systems was estimated by considering 16 h of daily operation. Table 8 summarizes the comparative evaluation of the performance and cost characteristics of the conventional cold storage and evaporative cooling systems.

A comparative study of performance between traditional cold storage (CS) and two stage indirect-direct evaporative cooling (EC) system was performed over several operational parameters. The EC system resulted in a significant reduction of 77.2% in heat load from 102,000 BTU/hr to 23,328 BTU/hr. Similarly, the daily energy usage was reduced by 76.14% from 150 kWh/day in CS to 35.79 kWh/day in the EC system. This demonstrates the great potential of EC systems to reduce operational costs in post-harvest storage. The EC system displayed improved ventilation performance with an air change rate of 86 ACPH, which was 115% higher than the CS's 40 ACPH, hence improving airflow homogeneity and lowering localised temperature gradients. Onion spoilage post-harvest was also reduced with rotting rates dropping from 25% to 15% suggesting a 40% increase in product preservation. The EC system was marginally economical in terms of operational costs (₹1,49,996/year versus ₹1,51,636/year) and reduced the annual maintenance costs by 60% (₹8,000/year versus ₹20,000/year). The EC system (8–10 years) was anticipated to have a little shorter lifespan than that of CS (10–12 years) but this is compensated by lower maintenance and energy requirements. Furthermore,

Table 7. Components and cost details

Sr. No.	Storage System	Equipment Details	Technical Features	Estimated Cost (INR)
1	Conventional refrigeration-based storage	Condensing system	8.5 TR capacity, Daikin unit with 9.50 kW rated power	114955
		Air circulation unit	3 HP blower, airflow rate of 84.95 CMM, Daikin DM 1-10-13 model, 380–415 V supply	50,215
		Moisture control unit	Industrial humidifier, 1 kW load, 180 m³/h air handling capacity	4,150
Overall system cost				**169320**
2	Indirect-direct evaporative cooling storage	Evaporative cooling assembly	3 HP HMX IDECool 6 unit, 84.95 CMM airflow capacity, suitable for 65.03 m² cooling area, power demand 2.1 kW	167474
Overall system cost				**167474**

Table 8. Comparative cost analysis for conventional cold storage and evaporative cooling system

Parameter	Conventional Cold Storage	Evaporative Cooling System	% Reduction/ Improvement
Heat Load	102,000 BTU/hr	23,328 BTU/hr	**77.2% Reduction**
Energy Consumption (kWh/day)	150	35.79	**76.14% Reduction**
Air Changes Per Hour (ACPH)	40	86	**115% Improvement**
Spoilage Rate (%)	25	15	**40% Reduction**
Operational Cost (INR/year)	₹1,51,636.	₹1,49,996	**1.08 % Reduction**
Annual Maintenance Cost (INR/year)	₹ 20,000	₹ 8,000	**60% Reduction**
Estimated System Lifespan (years)	**10-12 years**	**8-10 years**	**Slightly lower**
Electricity Price Sensitivity	High (100% grid dependent)	Moderate (Potential solar integration)	
Environmental Impact	**High (refrigerants, CO_2 emissions)**	**Low (water-based cooling, eco-friendly)**	
Initial Capital Investment (INR)	₹ 1,69,320 (condensing + AHU + humidifier)	₹ 1,67,474 (IDE Cooler)	**1.10 % Reduction**

the EC system is moderately sensitive to electricity rates, because it can be compatible with solar energy, whereas the CS system is completely dependent on the grid. The EC system is much more eco-friendly as it uses water-based cooling and no refrigerant, thus reducing CO2 emissions. Lastly, the EC system also had a slightly lower initial capital expenditure of ₹1,67,474 in comparison to the CS system that needed ₹1,69,320, making it a more affordable and sustainable solution for small scale farmers. Other economic aspects were also evaluated, in addition to the original capital and operational energy expenses provided above. Annual maintenance expenditures for conventional cold storage systems (including refrigerant refills, compressor service and annual equipment tests) are generally in the region of 8-10% of the initial equipment cost per annum. On the other hand, evaporative cooling systems require less maintenance typically 4 to 6% per year, mainly for pump maintenance, cooling pad replacement & water control.It is also important to consider the volatility of electricity rates as energy tariffs in India vary according to location and season. The study assumes an average electricity cost of ₹7.34/kWh. However, the sensitivity analysis indicates that a ±10% variation in electricity prices can lead to a change of about ±8–10% in the annual operating cost for conventional cold storage, and ±4–6% for evaporative cooling systems due to the latter's lower dependence on energy. System lifespan also impacts total cost-effectiveness. Conventional cold storage systems can last 12-15 years with appropriate maintenance and repairs, whereas evaporative cooling systems normally last 8-10 years depending on the location and water quality. These elements should be addressed in any long-term economic review or life-cycle cost analysis (LCCA).

CHALLENGES AND OPPORTUNITIES FOR ECS DEPLOYMENT IN DIVERSE CLIMATES

It is essential to explore the scalability and limitations of EC in various climatic regions to bring more practical significance to this work. Although EC has proved to be very energy efficient and cost effective in hot and arid conditions where the ambient humidity level is low, it cannot work well in hot and humid areas where the moisture-holding capacity of the air is already saturated. In such environments the temperature drop that may be achieved is restricted and may not be enough to preserve perishable goods effectively. In addition, the scale-up of EC to larger storage capacity requires careful design considerations related to airflow, water usage, and system maintenance. Water Availability is also an important element affecting scalability, especially in water-scarce locations. Also, connection with existing cold-chain logistics, and change of performance over seasonal climate variations, need to be addressed for consistent and reliable operation. Future research should focus on the development of adaptable and scalable hybrid cooling systems to improve the applicability of evaporative cooling in various climatic conditions for commercial applications.

CONCLUSION

Onion cultivation and storage is considered as major aspect of India's agriculture and is essential for its economy and food security. However, the supply chain continues to face challenges from continuous post-harvest losses due to limited storage capacity, spoilage and energy-intensive preservation methods. The study offers a deep dive into the performance of storage methods and shows that while conventional cold storage (CS) gives good preservation, its high capital and operational costs hinder access for small and marginal farmers. On the contrary, the two-stage indirect-direct evaporative cooling (EC) system evolved as an energy-efficient, cost-effective and sustainable alternative. The study verified the use of EC systems is able to maintain favourable storage conditions (~26.5 °C, 68% RH) to ensure the quality of the product for a 30-day storage period, using CFD-based modelling, experimental validation and energy-performance analysis. The system attained remarkable enhancements in airflow homogeneity, thermal stability and operating efficiency. Key quantitative discoveries are:

- Heat Load: decreased from 102,000 BTU/hr (CS) to 23,328 BTU/hr (EC) – 77.2% reduction
- Energy Consumption lowered from 150 kWh/day (CS) to 35.79 kWh/day (EC) - 76.14% reduction
- Air Changes per Hour (ACPH): 40 (CS) to 86 (EC) – 115% improvement
- Spoilage Rate: 25% (CS) to 15% (EC) - 40% decrease
- Weight loss at 30 days: 8.3% (CS) vs 6% (EC)
- 30 days sprouting: 15% (CS) vs 0% (EC)
- 30-day decay: 9% (CS) vs 0% (EC)
- Operational Cost: marginally cheaper - ₹1,49,996/year (EC) vs ₹1,51,636/year (CS)
- Annual Maintenance Cost: 60% less – ₹8,000 (EC) vs. ₹20,000 (CS)
- Initial Capital Investment: somewhat lower - Rs. 1,67,474 (EC) vs Rs. 1,69,320 (CS)
- Electricity Sensitivity: EC system allows for possible solar integration, but fully grid reliant cold storage does not
- Environmental Impact: EC has low environmental imprint (water based, refrigerant free) vs. CS (refrigerants, CO2 emissions)

The diffuser placement and the airflow velocities (0.2–0.5 m/s) were adequate to maintain the storage quality. The results of manual calculations, CFD simulations and experimental trials were compared and showed excellent agreement. The trustworthiness of this approach was proven. The EC system was proven to be functional but its dependence on the relative humidity level restricts its efficiency in particularly humid places. Future study should be addressed towards adaptive hybrid systems (combination of EC with auxiliary dehumidification), water efficient designs and IoT enabled smart control for broader applicability in varied agro climatic zones of India. The study shows a potential of well-designed evaporative cooling systems, coupled with verified CFD models and energy efficient methodologies to provide scalable, inexpensive and sustainable options for post-harvest onion storage. The wide-scale adoption of these technologies can contribute in significantly reducing post-harvest losses, stabilizing market prices and increasing the income of smallholder farmers across India.

NOMENCLATURE

EC	Evaporative cooling
CS	Conventional cold storage
U	Overall heat transfer coefficient (W/m^2 °C)
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
IIT	ndian Institute of Technology
CATARA	Centre for technology alternatives for rural areas
IACS	indirect air-cooling system
EC	Evaporative cooling
A	Surface area through which heat is transferred (m^2)
Tout	Temperature of outside air in °C
Tin	Temperature of inside storage space in °C
ho	Heat transfer coefficient on outer surface
hi	Heat transfer coefficient on inner surface
X_1, X_2	Thickness of wall, ceiling and insulating material respectively in meter
Ki	Thermal conductivity of wall and insulating materials (W/m°C)
Qp	Product load in kwh/Day
mp	Mass of product in kg
cp	Specific heat of product in kj/kg °C
Tenter	Entering temperature of product in °C
Tstore	Storing temperature of product in °C
QR	Respiration load in kwh/Day
QL	Lightning Load
n	Number of equipment's
t	Running time in hours
P	Power consumption in Watt
CMM	Air volume in cubic meter per minute
RSH	Room sensible heat in BTU/hr
ΔT	Room temperature-supply air temperature in °C
1.944	Constant based on air density under standard condition
AHU	Air handling unit
Ps	Total static pressure
η_m	Motor efficiency
η_b	Blower efficiency

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

REFERENCES

[1] Muhit AA, Islam MH, Husna A, Zereen I. Revolutionizing onion preservation: A novel aerated storage approach. Arch Agric Environ Sci 2024;9:329–335. [CrossRef]

[2] Priyanti D, Ayuningsih I, Rahmah ANF, Rahayoe S, Nugraha B. X-ray CT applications to reveal physical defects of onion during storage. AIP Conf Proc 2023;2700:04008. [CrossRef]

[3] Hon K, Jogas B, Wakte P, Padade S. Smart system for onion storage. Int Res J Mod Eng Technol Sci 2020;2:552–554.

[4] Panigrahi SS, Singh CB, Fielke J. CFD modelling of physical velocity and anisotropic resistance components in a peaked stored grain with aeration ducting systems. Comput Electron Agric 2020;179:105820. [CrossRef]

[5] Hong G, Peiser G, Cantwell MI. Use of controlled atmospheres and heat treatment to maintain quality of intact and minimally processed green onions. Postharvest Biol Technol 2000;20:53–61. [CrossRef]

[6] Wang Y, Lin Y, Chang H, Lai C. Ventilation pattern and heat dissipation characteristics of a vertical dry storage cask for spent nuclear fuel: Wind tunnel experiments and CFD simulations. Ann Nucl Energy 2021;160:108364. [CrossRef]

[7] Sim KS, Kim H, Hur SH, Na TW, Lee JH, Kim HJ. Geographical origin discriminatory analysis of onions: Chemometrics methods applied to ICP-OES and ICP-MS analysis. Food Res Int 2024;175:113676. [CrossRef]

[8] Guillamon Ayala E, Martín BD, Mut-Salud N, Ochando-Pulido JM, Morales-González JA, Arjona AB, et al. Optimization of an onion oil microemulsion by response surface methodology for enhanced physicochemical stability and biological activity. LWT 2024;194:115809. [CrossRef]

[9] Griffiths G, Trueman L, Crowther T, Thomas B, Smith B. Onions—a global benefit to health. Phytother Res 2002;16:603–615. [CrossRef]

[10] Carine Raddatz G, Sonza Pinto V, Queiroz Zepka L, Smanioto Barin J, José Cichoski A, de Bona da Silva C, et al. Use of red onion (*Allium cepa* L.) residue extract in the co-microencapsulation of probiotics added to a vegan product. Food Res Int 2022;161:111854. [CrossRef]

[11] Kiran PR, Aradwad P, AK TV, Nayana NP, CS R, Sahoo M, et al. A comprehensive review on recent advances in postharvest treatment, storage, and quality evaluation of onion (*Allium cepa*): Current status, and challenges. Future Postharvest Food 2024;1:124–157. [CrossRef]

[12] Lawande KE, Tripathi PC. On farm storage of onion and garlic: Success story. In: International Symposium on Edible Alliums: Challenges and Opportunities. Pune: Indian Society of Alliums; 2019.

[13] Torimiro N, Makinde IO, Omole RK, Daramola OB. Deterioration profile of postharvest onion (*Allium cepa* L.) bulbs induced by potential pathogenic microorganisms. Int J Pathog Res 2020;5:39–45. [CrossRef]

[14] Yeshiwas Y, Alemayehu M, Adgo E. The rise and fall of onion production; its multiple constraints on pre-harvest and post-harvest management issues along the supply chain in northwest Ethiopia. Heliyon 2023;9:e15905. [CrossRef]

[15] Anbukkarasi V, Paramaguru P, Pugalendhi L, Ragupathi N, Jeyakumar P. Studies on pre and post-harvest treatments for extending shelf life in onion: A review. Agric Rev 2013;34:256–268. [CrossRef]

[16] Author C. Long-time preservation and reporting of vegetables rotting and decay. South Asian J Eng Technol 2017;3:7–15.

[17] Sharma DK. Strategies for onion post-harvest diseases management. Asian J Res Bot 2023;6:279–300.

[18] Vitnor DS, Varma LR, Pawar Y. Influence of methods of harvesting and time of curing on yield and storage life of Rabi onion cv. Agrifound Light Red. Int J Curr Microbiol Appl Sci 2020;9:2007–2009.

[19] Opara LU. Onions: Post-harvest operation. In: FAO INPho - Post-Harvest Compendium. Rome: Food and Agriculture Organization of the United Nations; 2003. p. 1–17.

[20] Mejia J, Valembois V, Piret JP, Tichelaar F, Van Huis M, Masereel B, et al. Are stirring and sonication pre-dispersion methods equivalent for in vitro toxicology evaluation of SiC and TiC? J Nanopart Res 2012;14:815. [CrossRef]

[21] Dabhi M, Patel N. Effect of storage ventilation on bulb disease of onion. Adv Food Sci Eng 2017;1:100–106. [CrossRef]

[22] Chávez-Mendoza C, Vega-García MO, Guevara-Aguilar A, Sánchez E, Alvarado-González M, Flores-Córdova MA. Effect of prolonged storage in controlled atmospheres on the conservation of the onion (*Allium cepa* L.) quality. Emirates J Food Agric 2016;28:842–852. [CrossRef]

[23] Kate AE, Chakraborty SK, Pawar DA, Gorrepati K. Airflow resistance and pressure drop behavior in different conditions of bulk-stored onion and its dynamic modeling. J Food Process Eng 2019;42:e13141. [CrossRef]

[24] Imoukhuede OB, Ale MO. Onion storage and the roof influence in the tropics. Sky J Agric Res 2015;4:33–37.

[25] Priya EPB, Sinja VR, Alice RPJS, Shanmugasundaram S, Alagusundaram K. Storage of onions: A review. Agric Rev 2014;35:239–249. [CrossRef]

[26] Yadav RJ, Mahajani T, Kore SS, Gadhe PM, Kamble DA. Investigation of heat transfer characteristics using Fe3O4 nanofluid along with TT inserts in tube with uniform electromagnetic field. Appl Nanosci 2021;11:2759–2771. [CrossRef]

[27] Tripathi P, Lawande KE, Phule M, Vidyapeeth K, Tripathi PC. Designing and evaluation of onion storage structures for Indian conditions. Int J Agric Sci 2016;8:918–924.

[28] Selvam PT, Ahmed HI, Kumar SN, Kumaravelan R, Gandhi VCS. Design and development of modified air cooler cum storage system. Int J ChemTech Res 2014;6:1797–1801.

[29] Fonseca SC, Gil L, Manso MC, Cunha LM. Modelling the influence of storage temperature and time after cutting on respiration rate of diced red onions (*Allium cepa* L. cv. Vermelha da Póvoa). Postharvest Biol Technol 2018;140:27–33. [CrossRef]

[30] El Hourani M, Ghali K, Ghaddar N. Effective desiccant dehumidification system with two-stage evaporative cooling for hot and humid climates. Energy Build 2014;68:329–338. [CrossRef]

[31] Sharma S, Shukla R. Economics of storage of onion in Sikar district of Rajasthan. Econ Aff 2016;61:133–138.

[32] Sabaragamuwa R, Dharmasena D, Mannaperuma J. Optimization of environmental parameters for short-term storage of big onions and evaluation of the feasibility of controlled environmental storage. Trop Agric Res 2011;22:356–365. [CrossRef]

[33] Sibanda S, Workneh TS. Performance evaluation of an indirect air cooling system combined with evaporative cooling. Heliyon 2020;6:e03286. [CrossRef]

[34] Lv J, Yi J, Fu Y, Liu H. Experimental and numerical study of a multi-unit evaporative cooling device in series. Case Stud Therm Eng 2020;21:100727. [CrossRef]

[35] O'Sullivan JL, Ferrua MJ, Love R, Verboven P, Nicolaï B, East A. Forced-air cooling of polylined horticultural produce: Optimal cooling conditions and package design. Postharvest Biol Technol 2017;126:67–75. [CrossRef]

[36] Cui X, Islam MR, Mohan B, Chua KJ. Theoretical analysis of a liquid desiccant based indirect evaporative cooling system. Energy 2016;95:303–312. [CrossRef]

[37] Cuce PM, Riffat S. A state of the art review of evaporative cooling systems for building applications. Renew Sustain Energy Rev 2016;54:1240–1249. [CrossRef]

[38] Porumb B, Bălan M, Porumb R. Potential of indirect evaporative cooling to reduce the energy consumption in fresh air conditioning applications. Energy Procedia 2016;85:433–441. [CrossRef]

[39] Porumb B, Ungureşan P, Tutunaru LF, Şerban A, Bălan M. A review of indirect evaporative cooling technology. Energy Procedia 2016;85:461–471. [CrossRef]

[40] Grubben NLM, Keesman KJ. Modelling ventilated bulk storage of agromaterials: A review. Comput Electron Agric 2015;114:285–295. [CrossRef]

[41] Eshel D, Teper-Bamnolker P, Vinokur Y, Saad I, Zutahy Y, Rodov V. Fast curing: A method to improve postharvest quality of onions in hot climate harvest. Postharvest Biol Technol 2014;88:34–39. [CrossRef]

[42] Mishra R, Chaulya SK, Prasad GM, Mandal SK, Banerjee G. Design of a low cost, smart and standalone PV cold storage system using a domestic split air conditioner. J Stored Prod Res 2020;89:101720. [CrossRef]

[43] Akdemir S, Ozturk S, Edis FO, Bal E. CFD modelling of two different cold stores ambient factors. IERI Procedia 2013;5:28–40. [CrossRef]

[44] Vala KV, Makwana M, Sagarika N. Validation of evaporative cooling system using CFD analysis. Int J Curr Microbiol Appl Sci 2019;8:393–399. [CrossRef]

[45] Bhamare DK, Rathod MK, Banerjee J. Evaluation of cooling potential of passive strategies using bioclimatic approach for different Indian climatic zones. J Build Eng 2020;31:101356. [CrossRef]

[46] Tewari P, Mathur S, Mathur J, Kumar S, Loftness V. Field study on indoor thermal comfort of office buildings using evaporative cooling in the composite climate of India. Energy Build 2019;199:145–163. [CrossRef]

[47] Ko EY, Nile SH, Sharma K, Li GH, Park SW. Effect of different exposed lights on quercetin and quercetin glucoside content in onion (*Allium cepa* L.). Saudi J Biol Sci 2015;22:398–403. [CrossRef]

[48] Siddiqui JA, Ubale S. A computational study on comparative analysis of evaporative cooling system and conventional cold storage for onion preservation. Int J Refrig 2025;10:523–541. [CrossRef]