



RESEARCH ARTICLE

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DEVELOPMENT AND VALIDATION OF A THERMALLY STABLE SMALL-SCALE COLD STORAGE SYSTEM FOR ENHANCED POST-HARVEST PRESERVATION OF TOMATOES – EXPERIMENTAL AND NUMERICAL APPROACH

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ABSTRACT

Perishable agricultural commodities, which are subject to post-harvest depreciation, are a chronic problem in developing areas, which can be explained by the lack of cold-storage facilities, spatial variability of temperature patterns, and frequent power outages. The current study aims to design, optimize and experimentally test an improved small scale cold-storage facility that will improve uniformity of airflow, maintain thermal conditions and increase shelf life of tomatoes in decentralized rural environment. To make a comparison between conventional and curvature-modified cold-storage geometry, a three-dimensional Computational Fluid Dynamics (CFD) model was carried out based on the use of the SST k- ω turbulence model. The optimized design was installed in a cold-storage chamber of 8.42m³ with a 0.6TR vapor-compression refrigerator unit and 500-liter, water based thermal reserve. The results of CFD indicated an increase in penetration of airflow, a reduction in stagnant areas and a drop in local hot-spots temperature of 25-27°C to 22-25°C, accompanied by a reduction in precooling time of approximately 40 minutes. Conditions in experiments were also supported by experimental validation that kept temperatures at 11 $\pm$ 2°C, with relative humidity at 80-90% during a 28-day time interval. The stored tomatoes recorded the least weight loss of only 5.2% in the physiological weight and retained a pH between 4.3 and 5.9; whereas the tomatoes not stored withered after 12-13 days. The combined device was able to provide 15-20 hours of thermal reserve when the power went off. The current work validates that the application of CFD-based geometric optimization, coupled with thermal-back up, significantly improves cooling efficiency, stability in operation, and shelf-life conservation in a small-scale cold-storage facility.



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I. INTRODUCTION

Post-harvest loss remains a critical challenge in global food systems, particularly in developing countries where inadequate cold chain infrastructure significantly reduces the marketable yield of fruits and vegetables. Recent evidence indicates that insufficient temperature management and lack of decentralized storage facilities are major contributors to quantitative and qualitative losses in perishable commodities, directly affecting farmer income and food security [1], [2]. Smallholder farmers are disproportionately impacted due to limited access to reliable refrigeration, unstable electricity supply, and high capital costs associated with conventional cold storage systems, resulting in accelerated respiration, moisture loss, and microbial spoilage of produce shortly after harvest [3], [4]. Emerging research highlights that decentralized, small-capacity cold storage units equipped with improved thermal design and energy-efficient refrigeration can substantially reduce post-harvest deterioration by maintaining optimal temperature and humidity conditions at the farm level [5], [6].

Therefore, the development of compact, affordable, and thermally optimized cold storage systems is increasingly recognized as a strategic intervention for minimizing post-harvest losses, enhancing shelf life, and strengthening rural agricultural value chains in emerging economies. Temperature and relative humidity are the most critical environmental factors influencing the shelf life of fresh fruits and vegetables, as they directly regulate respiration rate, moisture loss, enzymatic activity, and microbial growth. Elevated storage temperatures accelerate metabolic reactions and increase respiration intensity, leading to faster ripening, softening, and nutrient degradation in perishable commodities such as tomatoes [7]. Conversely, maintaining produce within its recommended low-temperature range significantly slows biochemical deterioration and preserves physicochemical quality attributes during storage and distribution [8]. Relative humidity is equally important because inadequate humidity levels promote excessive transpiration and physiological weight loss, while excessively high humidity can enhance microbial proliferation and decay [9]. Recent postharvest quality modeling studies further demonstrate that precise control of combined temperature–humidity conditions stabilizes quality kinetics, extends marketable life, and improves overall storage performance in cold chain systems [4].

Therefore, optimized thermal and moisture management is fundamental for maximizing shelf life and maintaining the commercial and nutritional quality of fresh agricultural produce. Conventional cold storage systems often suffer from airflow heterogeneity due to poor internal design and non-optimized crate arrangements, resulting in stagnant zones and inconsistent convective heat transfer within the storage chamber [10]. Such non-uniform airflow patterns lead to uneven cooling and temperature gradients across stored produce, which can accelerate localized spoilage and reduce overall storage efficiency [11]. Additionally, in regions with unreliable electricity supply, frequent power outages disrupt thermal stability, causing temperature fluctuations that negatively affect product quality and shelf life [12]. These limitations highlight the need for improved airflow management and integrated thermal backup solutions in small-scale cold storage systems. Computational Fluid Dynamics (CFD) plays a vital role in optimizing cold storage systems by providing detailed insight into airflow behavior, temperature distribution, and convective heat transfer within complex storage geometries. Advanced CFD simulations allow researchers to evaluate the influence of fan configuration, evaporator placement, and product stacking on internal cooling performance, thereby identifying regions of thermal non-uniformity and inefficient circulation [13].

More recent numerical investigations demonstrate that CFD-guided design modifications can significantly reduce cooling time, improve temperature homogeneity, and enhance overall energy efficiency in refrigerated storage environments [10]. Thus, CFD serves as an essential predictive and optimization tool for designing high-performance cold storage systems with improved thermal reliability and product preservation capability. The latest developments in cold chain studies are focused on enhancing the thermal uniformity, energy efficiency and shelf-life maintenance with combined modeling and storage technologies. CFD methods have been broadly used to model airflow and heat-transfer in storage to optimize storage conditions; Laguerre et al. [14] have demonstrated that airflow distribution and time-temperature history are key factors in tomato cooling behaviour and aroma development, whereas Han et al. [15] have shown that intermittent warming can reduce chilling injuries and reduce energy consumption despite slight increases in mass loss. Expanding this insight, Han et al. [16] measured the effect of cold chain breaks, which they found to substantially amplify moisture loss and temperature inhomogeneity especially due to the relative humidity variability.

Phase change material (PCM) thermo-storage of thermal energy has become one of the main approaches to increase the reliability of cooling. You et al. [17] verified PCM plates that increased the cooling time by close to two hours with a simulation error of only 2.2, and Arun et al. [18] confirmed better cooling and reduced energy usage when PCM plates are placed strategically in the micro-cold storage. In a similar fashion, Natarajan et al. [19] have documented a 17.9% energy savings with a solar-PV-powered PCM-integrated system to be used in rural areas, and Prakash and Ravindra [20] increased PCM performance by integrating nanoparticles to be used in small-scale milk chilling. Other low-energy systems like evaporative cooling Siddiqui and Ubale, [21] greatly minimised the heat load and energy consumption than the traditional storage. Additional methods of preservation, such as the essential oil treatments Shehata et al., [22], also proved that synergistic methods can be used to prolong shelf life and lessen post-harvest losses. Taken together, these works indicate the significance of airflow optimization, integration of thermal storage, and the design of cold chains that are energy efficient in the development of sustainable cold chains.

Even though the problem of cold storage optimization has been studied extensively, most existing studies focus either on numerical airflow modeling, or on isolated experimental integration of thermal storage, and few have attempted to jointly consider the issue of geometric optimization, thermal backup systems, and shelf-life validation within a unified methodological approach. Furthermore, despite the studies of phase-change material (PCM) based and evaporative cooling systems, there is still an existing gap in the synthesis of computational fluid dynamics (CFD)-driven airflow modification using a field-deployable cold storage system with a water-based thermal backup to suit marginal farmers. This paper aims to fill that gap by combining three-dimensional CFD simulation of a curvature-adjusted geometry with the design and experimental validation of an 8.42m³ decentralized cold storage plant and at the same time evaluating its thermal behaviour and resultant tomato shelf life. This combination of numerical and experimental methodology therefore outlines a direct connection between improvement of airflow, thermal stability during power outages, and maintenance of post-harvest quality, which is a scalable, energy-efficient answer to small-scale agricultural situations.

II. NUMERICAL METHODOLOGY

The quantitative approach used in this study aims to analyze the airflow distribution and thermal processes in the traditional and optimized cold storage systems through the use of the Computational Fluid Dynamics (CFD). The three-dimensional modeling system was applied to model the convective heat transfer and to determine the effect of geometric changes on the uniformity of cooling and precooling.

II.1 COLD STORAGE GEOMETRY AND DESIGN

The numerical analysis was conducted on the two cold storage geometries which were made on the basis of 3D computer-aided design model to comply with the standard of small-scale storage.

The traditional model was made of a cuboidal chamber with internal dimensions of 2.4m x 1.95m x 1.8m and a total volume of around 8.42 m³ making it fit 1.875 tons of tomatoes. The evaporator unit was placed in the upper part of the rear wall and fitted with axial fans to aid forced circulation of air. To improve the evenness of the airflow and reduce the thermal stratification that was witnessed in the conventional design, a new design was proposed that has an internal curvature of 0.5 m at the evaporator wall and junction with the roof. This was an aerodynamic modification to minimize recirculation zones and enhance convective heat transfer. The tomato crates were made of food-grade plastic in grid form and spacing between rows and walls were spaced out to permit free passage of air. Figure 1(a) – Figure 1(b) presents CAD drawings of conventional and modified cold storage designs respectively.

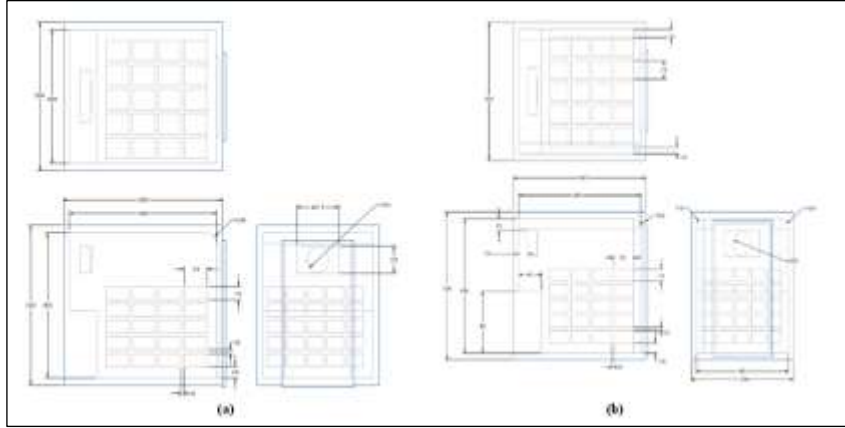


Figure 1: Geometry and design details of conventional and modified cold storage (a) CAD drawing of conventional design, (b) CAD drawing of modified design
Source: Authors, (2026).

II.2 GOVERNING EQUATIONS

Three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations were used to describe the airflow and heat transfer in the cold-storage chamber together with the energy equation. The continuity equation is a statement of the conservation of mass of incompressible flow:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

The RANS formulation was used to control the momentum transport in the refrigerated domain:

$$\rho \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{\partial (\rho u'_i u'_j)}{\partial x_j} \quad (2)$$

The equation of energy conservation of the transient heat transfer between air and stored produce is as follows:

$$\frac{\partial T}{\partial t} + u_i \frac{\partial T}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\lambda_{eff}}{\rho C_p} \frac{\partial T}{\partial x_i} \right) \quad (3)$$

The SST k- ω model was used to model the effects of turbulence, which is a combination of the near-wall accuracy of the k- ω formulation and the free-stream strength of the k- ϵ model. The turbulent viscosity is defined as:

$$\lambda_{eff} = \lambda + \frac{c_p \mu_t}{Pr_t} \quad (4)$$

This equation makes it possible to predict recirculation areas and thermal gradients in the storage chamber correctly.

II.3 COMPUTATIONAL DOMAIN AND MESH

The computational domain was the whole of the three-dimensional cold storage room with the air space, stacked tomato crates, and evaporator assembly and was represented using ANSYS Design Modeler to effectively represent spatial differences in airflow and heat transfer. A three-dimensional modeling strategy was used to solve the axial, transverse and vertical flow structures that would have otherwise not been sufficiently represented in the two-dimensional simulations. The discretization of fluid domain was done by the implementation of hybrid tetrahedra mesh that was local refined near the surfaces of crates and evaporator outlets to improve the representation of velocity gradients and convective heat exchange. The CFD model and the mesh structure are shown in Figure 2 of the report. The grid independence was checked through systematic mesh refinement until the changes in temperature and velocity fields were less than acceptable tolerance. The completed mesh had 130,471 nodes and 73,203 elements in the conventional cold storage arrangement, and 128,500 nodes and 71,848 elements in the modified arrangement, as shown in Table 3. This meshing approach therefore guaranteed numerical accuracy, stable convergence and predictability of airflow heterogeneity in the chamber.

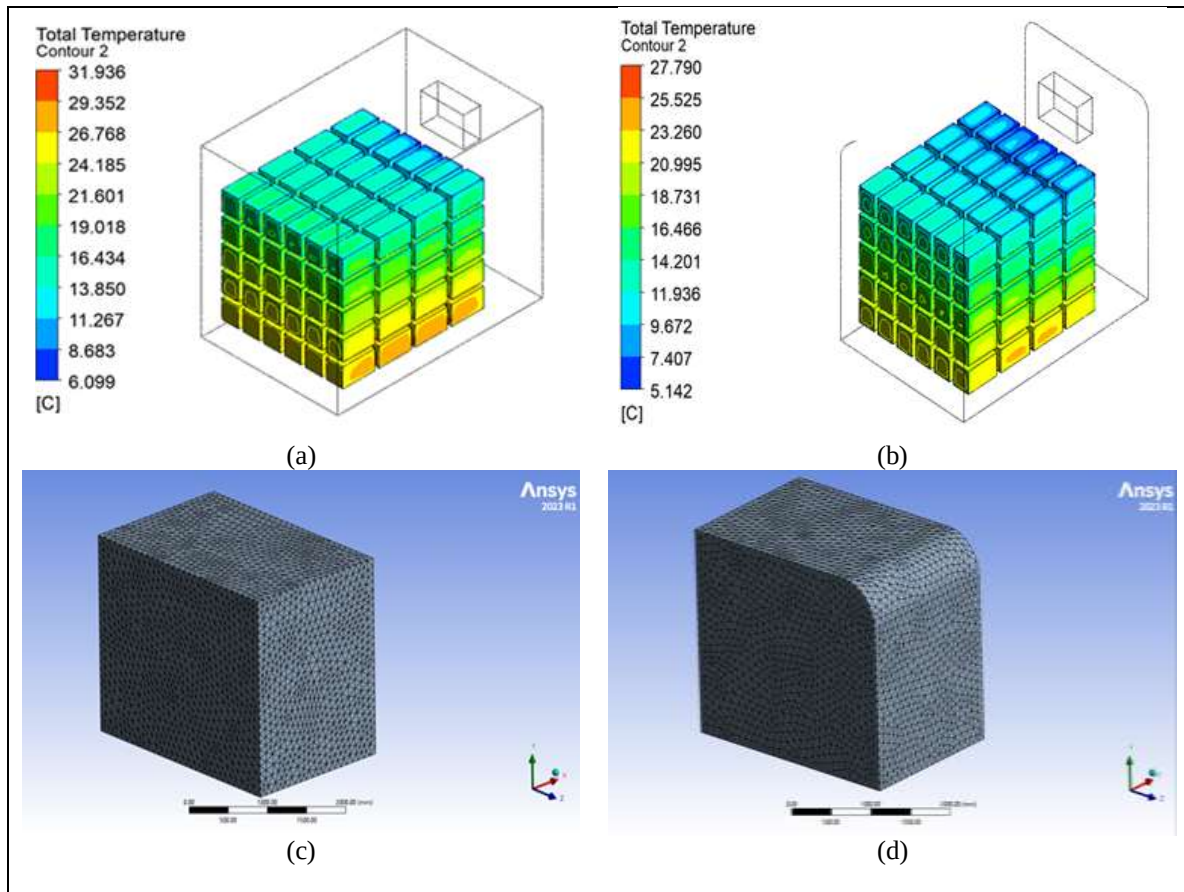


Figure 2: CFD model and meshing of cold storage (a) CFD model of conventional design, (b) CFD model of modified design, (c) Meshed model of conventional design and (d) Meshed model of modified design.

Source: Authors, (2026).

II.4 BOUNDARY CONDITIONS AND ASSUMPTIONS

Boundary conditions were defined in such a way that they realistically modeled the airflow and heat transfer in the cold storage chamber. The evaporator outlet was subjected to a velocity inlet boundary condition with an inlet air velocity of 1.5 m/s and turbulence intensity of 1% and the operating pressure was set to 101325 Pa. To precisely define the conditions of the inlet flow, the hydraulic diameter of the evaporator was considered to be 0.36 m. The numerical simulation assumed that thermo-physical properties of air and tomato remained constant during the simulation to simplify the model. Air properties were given as density of 1.293 kg/m³, specific heat capacity of 1004 J/kg-K and thermal conductivity of 24.07x10⁻³ W/m-K, and tomato properties as density of 1320 kg/m³, specific heat capacity of 2310 J/kg-K and thermal conductivity of 0.337 W/m-K as summarized in Table 2. The convergence was reached when the residual of continuity and momentum equations were less than 10⁻³ and energy residual was less than 10⁻⁶, thus, providing numerical accuracy and stability of the solution.

Table 1: Inlet parameters.

Parameter	Value
Operating Pressure	101325 Pa
Velocity Inlet	1.5 m/s
Turbulence Intensity	1 %
Hydraulic Diameter of Evaporator	0.36 m
Pressure Discretization	Standard
Momentum Discretization	Second Order
Turbulent Kinetic Energy (k)	First Order Upwind
Turbulent Dissipation Rate (ω)	First Order Upwind

Source: Authors, (2026).

Table 2: Model Parameters and Thermo-Physical Properties.

Parameter	Air	Tomato
Density (kg m ⁻³)	1.293	1320
Dynamic Viscosity (kg m ⁻¹ s ⁻¹)	1.72 × 10 ⁻⁵	—
Specific Heat (J kg ⁻¹ K ⁻¹)	1004	2310
Thermal Conductivity (W m ⁻¹ K ⁻¹)	24.07 × 10 ⁻³	0.337

Source: Authors, (2026).

II.5 SIMULATION PROCEDURE

ANSYS Fluent 21 was used to perform the numerical simulations to determine the distribution of airflow and temperature change within the cold storage chamber. A three-dimensional model was developed that was fully three-dimensional and the simulations were run at steady-state to study the airflow field and convective heat-transfer properties and transient simulations were run to study the cooling behaviour during the precooling stage. Pressure-velocity coupling was considered through the SIMPLE algorithm and second order discretisation schemes were applied to the momentum and energy equations in order to enhance numerical accuracy. The SST k- ω model was used to model turbulence to achieve near-wall flow behaviour. No-slip conditions were applied to all internal boundaries and each geometrical configuration was simulated separately. The convergence was achieved when the residuals were less than the tolerance limits set and thus guaranteed stable and reliable solutions. The model was validated through the comparison of the predicted airflow and temperature fields with those found in previous experimental studies of cold-storage chambers, thus giving confidence in the numerical framework.

III. EXPERIMENTAL METHODOLOGY

The current experimental approach was designed to confirm the thermal performance and storage effectiveness of the small-scale cold storage system developed under the realistic operating conditions. The section outlines the system development, estimation of refrigeration load, instrumentation design, and quality evaluation procedures used in evaluating the shelf-life extension of stored tomatoes.

III.1 DEVELOPMENT OF IMPROVED COLD STORAGE SYSTEM

A small-scale, improved on-field cold storage facility with an internal volume of 8.42 m³ (2.4 m x 1.8 m x 1.95m) was designed to store 500 kg to 1 ton of perishable produce under controlled temperatures. The storage chamber was made of 100 mm thick polyurethane (PU) insulated panels bonded to pre-painted galvanized iron (PPGI) sheets, which were used to reduce conductive heat gain and at the same time increase structural durability. To achieve a target storage temperature of 11±0.2°C, a 0.6TR vapor-compression refrigeration (VCR) system using R134a as a refrigerant was installed. The refrigeration system included a hermetic compressor, air-cooled condenser, evaporator and a thermostatic expansion valve, the specifications of which are shown in Table 1. In order to reduce the effects of rural power outages, a 500-liter water tank was added as a secondary, refrigerant-based thermal backup that would be able to support cooling functions during load-shedding events. Moreover, a humidifier was placed at the center of the storage chamber to maintain the relative humidity of the chamber at 80-90% to minimize physiological weight loss in the stored tomatoes. The general system layout, such as the layout of crates, is shown in Figure 2.

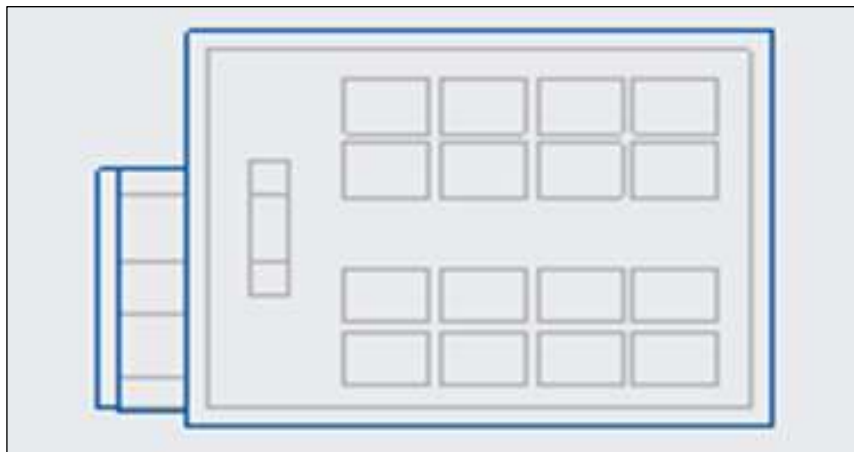


Figure 3: Layout of modified cold storage (top view)

Source: Authors, (2026).

Table 3: Specification of Basic Component of VCR system.

Component	Model	Capacity	Make	Additional Info
Hermetic compressor	RS53C1E-LC	0.6 -ton Ref	Emerson Copeland	Efficient and reliable
Evaporator	EKF Series	7 kW	Emerson Copeland	Proper air circulation
Air-Cooled Condenser	ECO series	2.5 to 3.5 kW	Emerson Copeland	Temp range 20°C to 45°C
Thermostatic Expansion Valve	TXV Valve - EX2	0.6 -ton Ref	ALCO HF Series	adjusts refrigerant flow
Water Circulation Pump	Mini 50S	200 Lit/hr	Kirloskar	Reliable
Humidifier	HUL585B	5 lit	Honeywell	Filter-free

Source: Authors, (2026).

III.2 REFRIGERATION LOAD CALCULATIONS

The refrigeration capacity of the developed cold storage system was determined by evaluating all major heat gains acting on the chamber. The transmission load through the walls, roof, and floor was calculated using:

$$Q_T = \frac{UA(T_o - T_i) \times 24}{1000} \quad (5)$$

Where U is the overall heat transfer coefficient, A is the total surface area, T_o is ambient temperature, and T_i is storage temperature. The sensible heat load of the agricultural product during pull-down was estimated as:

$$Q_p = \frac{m c_p (T_{enter} - T_{store})}{3600} \quad (6)$$

Where m is product mass and c_p is specific heat capacity. The respiration load of tomatoes was computed using:

$$Q_R = \frac{m_{ag} h_r}{24 \times 60 \times 60} \quad (7)$$

Where h_r represents respiration heat. Internal loads due to lighting, personnel activity, equipment, and infiltration were added to determine the total heat load of 16.72 kWh/day. Based on this cumulative load, the theoretical refrigeration requirement was approximately 1.4 kW (0.4–0.5 TR), and a 0.6 TR VCR system was selected to ensure operational safety and stability. Figure 4 depicts heat load of cold storage.

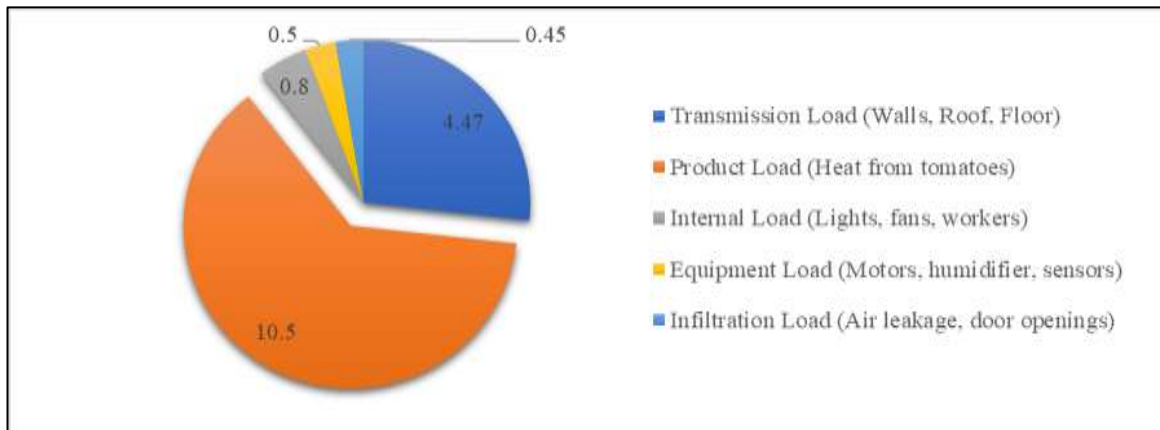


Figure 4: Heat load of cold storage.

Source: Authors, (2026).

III.3 EXPERIMENTAL SETUP AND INSTRUMENTATION

The experimental test setup was designed to test the thermal stability and storage capacity of the cold storage system developed in terms of real operational conditions. To monitor the real time temperature and relative humidity, a digital data logger (Elitech GPS-6) was used to capture the sensor coupled values in the storage chamber. The grid mode system was used and experiments conducted in one month where 500 kg of tomatoes was used as a test commodity. Figure 3 shows the schematic diagram and the photo image of experimental set up in Eco-Saras Company, Dehu-Pune, India. The monitoring was done on a regular basis over the 28 days of storage and data gathered at a specific time period to check on the ambient temperature, internal storage temperature and humidity conditions. The shelf life of tomatoes kept in the cold chamber was contrasted with the samples that were kept at ambient, non-storage conditions. Chemical quality parameters (total soluble solids, pH) and the physical parameters (physiological loss of weight) were measured at the end of the storage period. There was also visual observation and sensory assessment to establish the alteration of colour, feel and smell of the stored and non-stored samples.



(a)



(b)

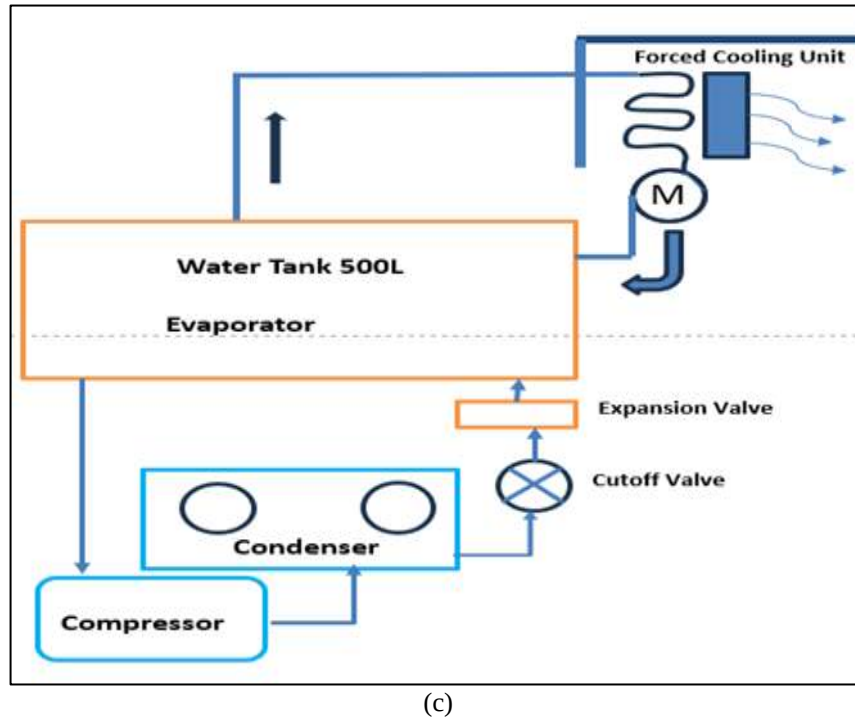


Figure 5: Experimental test setup (a) Exterior view of cold storage, (b) Interior view of cold storage (c) Flow diagram of cold storage
Source: Authors, (2026).

III.4 QUALITY ASSESSMENT METHODS

Physiological, chemical and sensory parameters were used to assess the quality of stored tomatoes to determine the effectiveness of the developed cold storage system. Physiological Loss in Weight (PLW) was determined with the help of a standardized digital weighing balance in terms of recording the initial and final weights of sampled tomatoes during the storage period of 28 days. The weight loss was computed by using the percentage weight loss as:

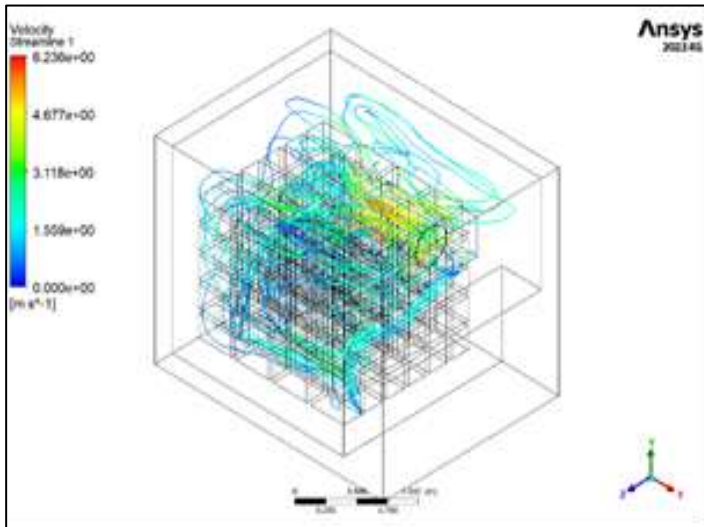
$$PLW(\%) = \frac{W_i - W_f}{W_i} \times 100 \quad (8)$$

Where W_i is the initial weight and W_f is the final weight of the sample. The change in weight of stored tomatoes and non-stored tomatoes was measured. The chemical quality was measured by comparing the pH using a pen-type digital pH meter (Model PH-009(I)A) at pre-established time intervals to check the changes in acidity in the course of storage. The longitudinal change of pH values was recorded. Also, visual and sensory tests were conducted to evaluate colour, firmness, epidermal condition, odour and texture.

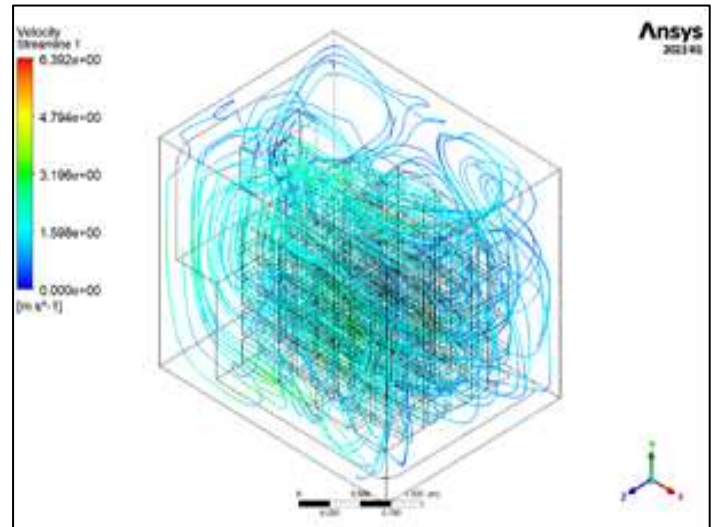
IV. RESULTS AND DISCUSSIONS

IV.1 CFD SIMULATION RESULT

The computational fluid dynamics simulations indicated a stable and consistent numerical convergence as scaled continuity, momentum, energy, and turbulence-related variables all showed a steady decrease in magnitude to consistent low values after approximately 100 iterations as shown in Figure 3. This intersection confirms the accuracy of the numerical algorithm and the suitability of the selected turbulence model in proper predictions of airflow and heat transfer in the chamber. Streamline analysis revealed that both designs had a top-to-bottom circulatory trend, but the altered cold-store design had smoother flow paths, reduced vortices, and less recirculation areas near the upper corners as shown in Figure 4. Velocity-contour plots also highlighted greater airflow penetration between the rows of the crates in the modified design, and thus reduced stagnant areas that were evident in the cuboidal design (Figure 5). Comparative temperature-contour analysis indicated a more uniform thermal field in the altered configuration, whereby the number of high temperature loci at the ceiling was less and the overall amount of heat removed in the storage volume was more effective (Figure 6). According to the summary of Table 4, the altered design reduced the hot-spots temperature to approximately 22-25°C, created a more flattened temperature gradient, and reduced the precooling time by almost 40 minutes, without compromising on the improved core-product temperature uniformity. These findings prove that internal curvature introduction enhances uniformity in airflow and general cooling.

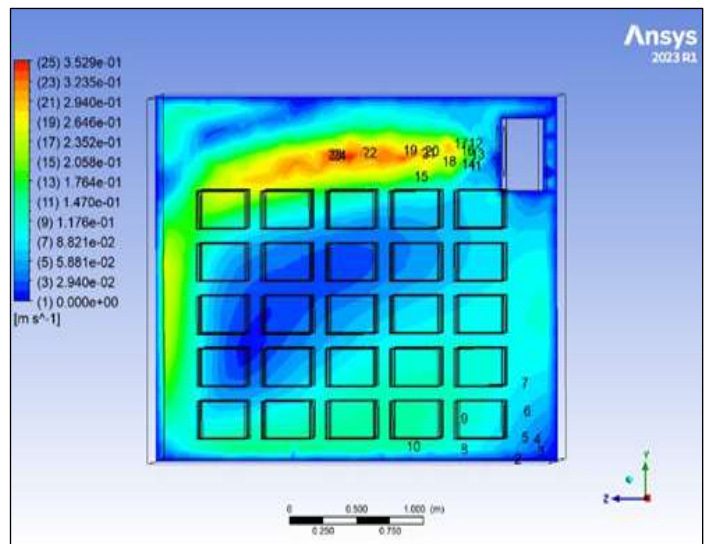


(a)

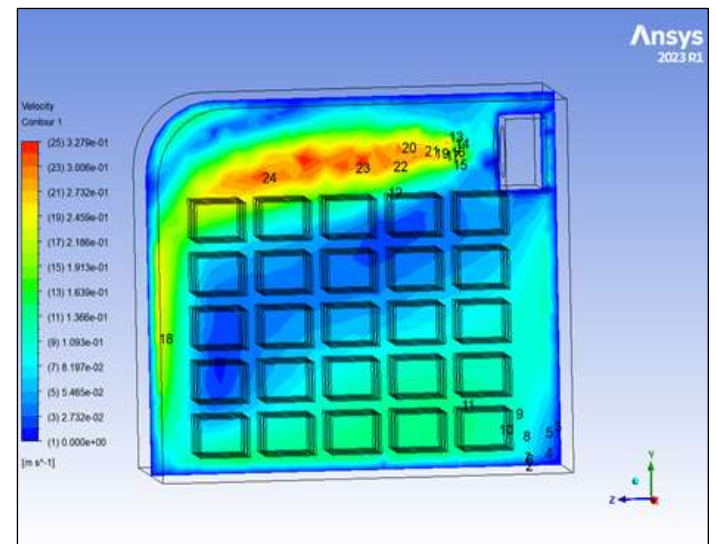


(b)

Figure 5: Streamline contour of (a) conventional and (b) modified cold storage design
Source: Authors, (2026).

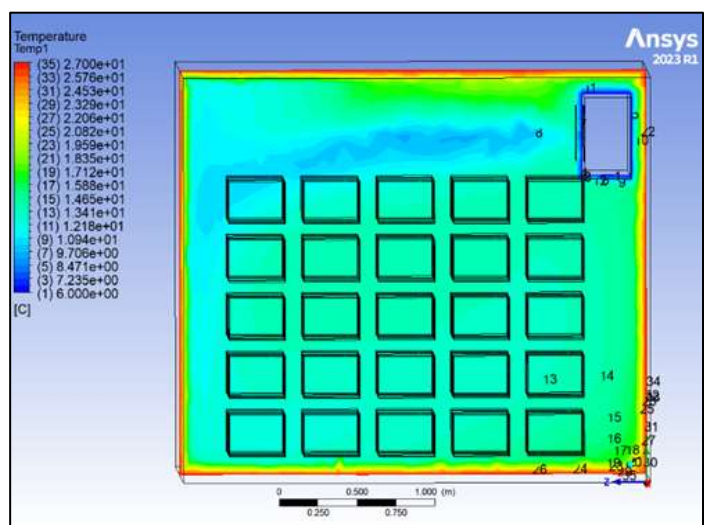


(a)

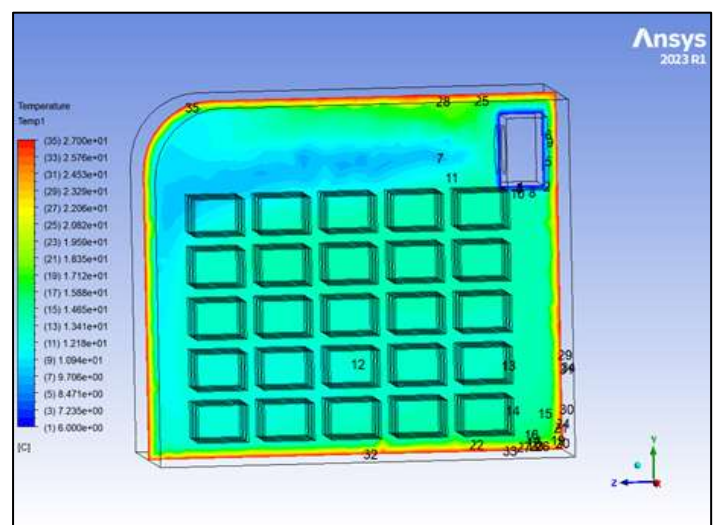


(b)

Figure 7: Velocity contour (a) Conventional cold storage, (b) Modified cold storage
Source: Authors, (2026).



(a)



(b)

Figure 8: Temperature distribution (a) Conventional cold storage (b) Modified cold storage
Source: Authors, (2026).

Table 4: Comparative of CFD simulation of both cold Storage.

Aspect	Regular Cuboid Cold Storage	Modified Cold Storage
Consistency of Cooling	Reasonable, with high-temp sectors	Improved, more uniform temperature circulation
Hot spot	25–27°C (upper right and top corners)	22–25°C (top corner only)
Core Product Temperature	9–13°C	8–12°C
Temperature Gradient	Sharp gradient from center to ceiling boundaries	Flatter gradient, less heat penetration
Overall Efficiency	Lower (inefficient circulation near top)	Higher (better air flow and heat removal)

Source: Authors, (2026).

IV.2 THERMAL STABILITY ANALYSIS

The thermal stability of the developed cold storage system was checked under the conditions of the continuous operation to determine its ability to provide the controlled environmental conditions. Figure 8 shows a temperature change in the chamber throughout the operation, which shows that the temperature in the storage was kept at $11 \pm 2^\circ\text{C}$, with minimum variation regardless of the changes in ambient conditions. The stability trend shows that the compressor is cycling and insulating effectively thus maintaining consistency in cooling over the storage time. The conditions of relative humidity in the chamber were also monitored and the results depicted in Figure 5 shows that the humidity was managed at the desired range of 80-90% due to the integrated humidifier functionality. This controlled humidity condition reduced the loss of moisture in tomatoes stored and minimized physiological degradation. Performance of the system during short-term power outages was also studied and the availability of the thermal back up system of 500 liter water based helped in slow rise of the temperatures instead of sudden thermal peaks. Figure 6 shows the load shedding temperature profile, which proved that the backup system was effective in postponing temperature increase, therefore maintaining the quality of products. In general, the outcomes confirm the hypothesis that the enhanced cold storage system preserves the thermal stability within the realistic working conditions.

IV.3 SHELF –LIFE PERFORMANCE EVALUATION

The shelf-life performance of tomatoes that were exposed to the improved cold-storage system was evaluated by systematic comparison of weight loss, pH change, and sensory attributes with non-stored controls. The mass change of the tomatoes stored over the 28-day storage period as shown by Figure 9 indicates that stored tomatoes underwent a gradual change of about 110g to 104g, and non-stored samples underwent a sharp decrease to almost 70g. This difference shows that the controlled temperature regime ($11 \pm 2^\circ\text{C}$) and relative humidity that was kept at 80-90% greatly reduced physiological weight loss. The pH changes as seen in Figure 9 also supports the stabilizing effect of cold storage. Although non-stored tomatoes exhibited a high degree of pH fluctuation of 4.2 to 5.7 over the initial two weeks, cold-stored samples had a relatively stable pH range of 4.3 to 5.9 over the entire period of storage. This trend shows that the rate of ripening is delayed and the metabolic activity is reduced in the controlled conditions. Table 5 summarizes visual and sensory observations that indicated that stored tomatoes maintained their firmness, shape and skin integrity without wrinkles even after 28 days, but non-stored tomatoes decayed after 12-13 days. The preserved texture and low off-odour of the stored samples also show that quality attributes were preserved.



Figure 9: (a) Weight Measurement of Tomato Samples (b) Marking of Tomato Samples (c) Tomato storage in cold-storage (d) Reading markings on tomato.

Source: Authors, (2026).

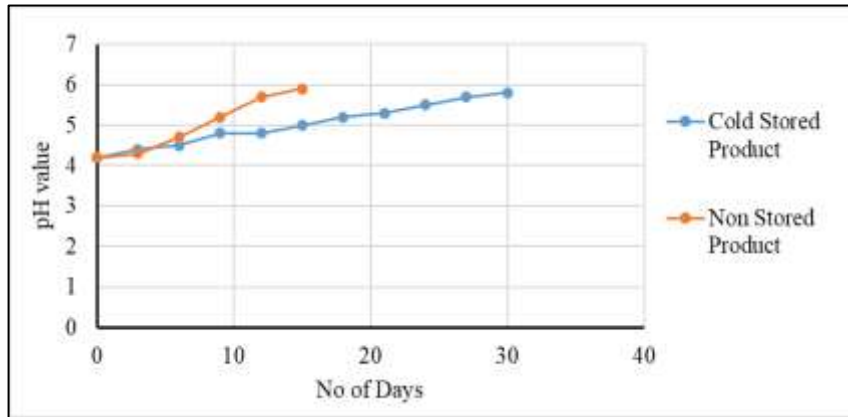


Figure 10: Comparison of pH variation over time.

Source: Authors, (2026).

Table 5: Visual and Sensory Observation of stored and non-stored tomato.

	Product Features	Non-Stored	Stored
Days		After 12-13 Days	After 28 Days
Visual Appearance	Color	Red	Dark Red
	Shape & Firmness	Shrinkage, Softening	Same Shape & Firm
	Skin Condition	Wrinkles	No wrinkles
Sensory Assessment	Odor	Off-odors	Little off-odors
	Texture	Mealiness	Juicy texture

Source: Authors, (2026).

V. CONCLUSION

This study presented the design optimization and experimental validation of an improved small-scale cold storage system integrating Computational Fluid Dynamics (CFD) analysis with a vapor compression refrigeration system and thermal backup mechanism. The objective was to enhance airflow uniformity, maintain thermal stability during power interruptions, and extend the shelf life of tomatoes under decentralized rural storage conditions.

- The CFD-based curvature modification significantly improved airflow distribution, reduced recirculation zones, and minimized temperature gradients inside the storage chamber.
- The modified geometry reduced precooling time by approximately 40 minutes and lowered localized hot spot temperatures compared to the conventional design.
- The developed 8.42 m³ cold storage unit equipped with 100 mm PU insulation and a 0.6 TR VCR system successfully maintained storage conditions at $11 \pm 2^{\circ}\text{C}$ and 80–90% relative humidity.
- The integration of a 500-liter water-based thermal backup system effectively mitigated temperature spikes during power interruptions, ensuring stable storage conditions for 15–20 hours.
- Shelf-life evaluation demonstrated that stored tomatoes exhibited only 5% weight loss and maintained acceptable pH stability over 28 days, whereas non-stored samples deteriorated within 12–13 days.
- The system demonstrated operational feasibility and energy adequacy for decentralized, on-field applications, offering a practical solution for reducing post-harvest losses.

Overall, the integrated numerical–experimental approach confirms that airflow optimization combined with thermal backup integration significantly enhances cold storage performance and post-harvest preservation efficiency.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Milind Sadashiv Swami, Manoj Ramesh Dahake.

Methodology: Milind Sadashiv Swami, Manoj Ramesh Dahake.

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