

Performance and Economic Evaluation of a Zero-Energy Evaporative Cooling Chamber for Post-Harvest Storage of Green Chilli

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Abstract

Post-harvest losses of green chilli (*Capsicum annuum* L.) remain a significant problem for smallholder farmers in Bangladesh due to the absence of affordable cold storage infrastructure. In this study, we designed, constructed, and evaluated the performance of a zero-energy evaporative cooling chamber fabricated from locally available sand bricks and river-bed sand as the cooling medium. The structure ($155 \times 63 \times 80$ cm³) operated on the principle of evaporative cooling (EC) without any electrical input. Under no-load conditions, the chamber achieved a maximum temperature drop of 10°C at midday. During a 10-day green chilli storage trial, the average internal temperature was 21.1°C with an average relative humidity of 80.1%, compared to ambient conditions of 20–33°C and 45–81% relative humidity. Physiological weight loss inside the chamber reached only 12.4% after ten days, significantly lower than 35.4% observed under ambient conditions and comparable to the 8.5% recorded in a refrigerator at 3°C. Chilli firmness, assessed qualitatively through visual and photographic observation, was notably better maintained in EC storage than under ambient conditions throughout the 10-day period. The total construction cost was estimated at 6,800 Tk for the first year, with only minor recurring costs for annual roof maintenance and daily operating labour. The technology represents a promising, low-cost post-harvest storage option for smallholder farmers in tropical regions, though further evaluation across multiple seasons and locations is warranted.

Keywords: Firmness, Humidity, Loss reduction, Low-cost technology, Storage quality

Abbreviations

Abbreviation	Full Form
ZECC	Zero-Energy Cool Chamber
EC	Evaporative Cooling
DBT	Dry-Bulb Temperature
Tw	Wet-Bulb Temperature
RH	Relative Humidity
SE	Saturation Efficiency (Cooling Efficiency)
PLW	Physiological Loss of Weight
BDT	Bangladeshi Taka (currency)
LMICs	Low- and Middle-Income Countries
IARI	Indian Agricultural Research Institute

Introduction

Green chilli (*Capsicum annuum* L.) is a perishable horticultural commodity widely cultivated and consumed across South and Southeast Asia. All over the world, almost 400 different varieties are cultivated (Hossen, 2015); among them, about 32 local varieties are

grown in Bangladesh (Bangladesh Bureau of Statistics [BBS], 2019). In the year 2023-24, its production reached around 748 thousand tonnes (BBS, 2025). However, post-harvest losses remain disproportionately high, largely because smallholder farmers lack access to affordable cold storage facilities. Physiological deterioration, microbial spoilage, and weight

loss owing to moisture evaporation are the principal mechanisms driving these losses (Shezi, Ngcobo, Khanyile, & Ncama, 2024). Temperature, relative humidity, variety, and stage of ripening are recognised as the primary environmental factors governing the shelf life of green chilli (Kapoor, Sidhu, Tandon, Jindal, & Mahajan, 2022; Tivalli, Kusumiyati, Anwar, Maqbool, & Islam, 2026). Global estimates indicate that fruits and vegetables collectively incur post-harvest losses ranging from 28% to 55% of total production, accounting for approximately 750 billion USD per annum (Karoney, Molelekoa, Bill, Siyoum, & Korsten, 2024). In low- and middle-income countries (LMICs) lacking access to reliable cold chain infrastructure, losses can reach 50% or more of fresh produce before it reaches the consumer (Defraeye, Shoji, Onwude, & Shrivastava, 2023). These losses translate directly into reduced farmer income, aggravated food insecurity, and increased nutritional deficits, particularly where fresh vegetables constitute the primary dietary source of vitamins and minerals (Twum-Dei, Lutterodt, Annan, & Aduku, 2025). Similarly, Ghana alone has reported post-harvest losses ranging from 30% to 50% across the value chain (Twum-Dei *et al.*, 2025). Temperature fluctuations alone have been estimated to cause 25-50% of post-harvest losses in pepper fruits (Obayelu, Adegboyega, Sowunmi, & Idiaye, 2021).

Mechanical refrigeration is widely recognised as the most effective physical method for post-harvest loss mitigation; however, it demands substantial capital investment and a reliable electricity supply. Chopra *et al.* (2022) reported that evaporatively cooled (EC) storage systems are relatively less expensive than other storage methods. In rural Bangladesh, as in many other developing countries, farmers often have limited financial capacity to invest in postharvest storage technologies. Therefore, sustainable, low-cost, off-grid alternatives may help address the cold-chain gap at the farm level (Pawar & Haribhakta, 2024). The evaporative cooling (EC) technique exploits the latent heat of water vaporisation. As liquid water evaporates from a

porous cooling medium into the surrounding air, it absorbs heat from the air, lowering the dry-bulb temperature of the immediate environment while raising its relative humidity. This adiabatic process requires no mechanical energy input when operated passively, making it particularly attractive for off-grid, resource-limited settings (Vala, Saiyed, & Joshi, 2014). Defraeye *et al.* (2023) systematically mapped the deployment potential of passive evaporative coolers across India and Nigeria and demonstrated that meaningful gains in post-harvest life could be achieved across these regions. The cooling benefit is greatest where the wet-bulb depression is largest, i.e., where ambient temperatures are high and ambient relative humidity is low.

The conceptual framework of the Zero-Energy Cool Chamber (ZECC), originally developed at the Indian Agricultural Research Institute (IARI), has been shown to extend the shelf life of fruit crops under semi-arid conditions in Western India (Singh *et al.*, 2010). The term "zero-energy" refers specifically to the absence of electrical or mechanical energy input; the system nonetheless requires a continuous supply of water to maintain the wetted cooling medium, which may itself be a constraint in some rural or water-scarce contexts, particularly during dry seasons when irrigation and domestic water demands compete for limited supply. The chamber required approximately 270 L of water per day (based on the 90 L reservoir refilled three times each day), or about 27 L kg⁻¹ of stored produce. This is modest compared to typical farm water use, but could still be a challenge for farmers without easy access to a water source like a tube well or pond, especially in the dry season. Mishra, Jha, and Ojha (2020) measured the physiological loss of water (PLW) and vitamin C of vegetables under different storage conditions. More recently, Kumbhakar, Mukherjee, and Ghosh (2023) reviewed ZECC applications and confirmed that the double-walled, sand-filled structure remains the most cost-effective refrigerant-free storage technology available to smallholder farmers in tropical climates. Kenghe, Fule, and Kenghe (2015) evaporative

cooler was designed and a maximum storage life of 16 days was found in coconut coir.

Despite this body of evidence, the systematic evaluation of ZECC technology specifically for green chilli storage under the humid subtropical climatic conditions of Bangladesh remains limited. Bangladesh's climate, characterised by moderate wet-bulb depression during the dry winter months (November–February), may offer sufficient psychrometric conditions for effective passive cooling. The present study was conducted during a single 19-day window during the winter period (9–26 November 2020); the reported thermal and quality performance therefore reflects conditions specific to this window and may not represent the full Nov–Feb winter season. [Wike et al. \(2023\)](#) highlighted the recent advances in evaporative cooling specifically for short-term post-harvest cooling of fruits and vegetables and identified the need for location-specific field evaluations using locally available construction materials. The present study addresses this gap by constructing a fully passive, zero-energy evaporative cooling chamber from sand bricks and river-bed sand, both abundantly available in Bangladesh, and rigorously evaluating its thermal performance and its effect on the post-harvest quality of green chilli.

Materials and Methods

Design Principles

The cooling chamber was designed on the principle of direct evaporative cooling. Water is dripped continuously onto a river-bed sand pad via a perforated distribution pipe. As warm ambient air passes through the wetted sand, sensible heat is transferred to the water, which evaporates and increases the relative humidity of the airstream while reducing its dry-bulb temperature. Effective cooling is promoted by high ambient dry-bulb temperature, low relative humidity, continuous water supply, and adequate natural airflow through the structure.

Design Assumptions

The following design constraints were adopted: (i) the structure must be located in a shaded position to minimise direct solar radiation gain; (ii) continuous water flow through the cooling medium must be maintained; (iii) the cooling medium must possess adequate water-retention capacity and must be locally available; and (iv) all construction materials must be non-corrosive, durable, and obtainable at a low cost. The chamber's dimensions, wall configuration, and water discharge rate were adapted from established zero-energy cool chamber design principles ([Roy & Khurdiya, 1986](#)) and scaled for a pilot-scale experimental capacity of approximately 10 kg, rather than derived from a formal engineering design calculation.

Construction of the Cooling Chamber

The experimental chamber was constructed at the Department of Farm Power and Machinery, Sylhet Agricultural University, Sylhet, Bangladesh (Figure 1). The structure measured 155 × 63 × 80 cm (length × breadth × height) and comprised a double cavity wall of sand bricks, with river-bed medium fine sand, a locally available, highly porous sand grade, filling the inter-wall cavity. Water drawn from a tube well at the experimental site was used to fill a 90-L overhead reservoir, which was manually refilled three times daily. A black PVC pipe of 1.27 cm nominal diameter, connected to the reservoir, distributed water through 2.54 cm-spaced drip beads at a discharge rate of 30 L h⁻¹ onto the sand-filled cavity walls, keeping the cooling medium continuously wetted. Ambient air passed through the porous, wetted sand cavity walls by natural diffusion, losing sensible heat and gaining moisture in the process; the resulting cooler, more humid air then occupied the internal storage chamber, creating a favourable microclimate for the stored produce. A bamboo-and-straw roof cover provided shade and reduced direct solar gain.



(a)



(b)



(c)



(d)

Fig. 1. Construction stages of the zero-energy evaporative cooling chamber. (a) Double cavity brick wall under construction, showing river-bed sand being packed into the wall cavity as the cooling medium; (b) Perforated PVC distribution pipe positioned along the top of the cavity wall to enable continuous drip wetting of the sand; (c) Completed chamber structure with bamboo-framed roof cover installed to provide shade and reduce direct solar radiation gain; and (d) Close-up of the straw thatching material used for the roof cover, providing additional insulation and shading

Cooling Medium

Medium fine river-bed sand was selected as the cooling medium based on its porosity, water-retention capacity, high evaporation rate, local availability, and low cost. Sand of this grade has been reported to maintain sufficiently high moisture content throughout the operation of passive evaporative coolers (Vala *et al.*, 2014).

Experimental Procedure and Performance Evaluation

The experiment comprised two sequential phases: a no-load phase (8 days, 9-16 November 2020) and a load phase (10 days, 17-

26 November 2020). In the no-load phase, the chamber was operated without stored produce to characterise the intrinsic thermal performance. In the load phase, approximately 10 kg of freshly harvested, mature green chilli (a local market variety, *Capsicum annuum* L., with no specific registered cultivar designation) was obtained directly from a local farm on the first day of the load phase (17 November 2020). Maturity was assessed visually based on typical market-ready characteristics (full-pod size, firm texture, and uniform green colour). The chilli was placed on a rack inside the chamber, without additional packaging or containment,

and monitored daily throughout the 10-day trial. Approximately 10 kg of green chilli was procured as a single batch on the first day of the load-phase trial and divided into three portions on the same day, which were allocated to the evaporative cooling chamber, the ambient open-air control, and the refrigerator, respectively. Each treatment was conducted as a single trial without independent replication; therefore, the results presented are descriptive and comparative rather than derived from replicated statistical analysis. The no-load phase preceded the load phase to characterise the chamber's intrinsic cooling performance independent of the confounding effects of produce respiration heat and moisture release, and to verify that the chamber reliably achieved favourable storage conditions prior to introducing perishable produce.

Dry-bulb temperature (DBT) and wet-bulb temperature (T_w) were measured at three points every day (09:00, 12:50, and 16:00) using generic mercury-in-glass thermometers (measurement range: -40°C to 50°C ; 1°C graduation; manufacturer accuracy not specified). One thermometer was placed outside the chamber (ambient) and a second inside the storage space. Outside and inside readings were recorded simultaneously at each of the three daily time points to ensure valid paired comparisons for the cooling efficiency calculation. Relative humidity (RH) was measured using a digital hygrometer (model HTC-2; measurement range: 10-99% RH; accuracy: $\pm 5\%$ RH). Wet-bulb temperature was cross-checked using a standard psychrometric chart.

Cooling efficiency (saturation efficiency, SE) was calculated according to Harris (1983):

$$SE = \frac{(T_{1db} - T_{2db})}{(T_{1db} - T_{1w})} \times 100 \quad (1)$$

where T_{1db} is the outside ambient dry-bulb temperature ($^{\circ}\text{C}$), T_{2db} is the inside chamber dry-bulb temperature ($^{\circ}\text{C}$), and T_{1w} is the outside wet-bulb temperature ($^{\circ}\text{C}$).

Physiological weight loss was assessed daily using a digital balance (Jadever, FPH series; weighing capacity: 1 kg; resolution: 0.1 g).

Three storage treatments were compared: (i) evaporative cooling chamber, (ii) ambient open-air storage (control), and (iii) refrigerator at a constant temperature of 3°C . The ambient open-air control was located outdoors in the immediate vicinity of the evaporative cooling chamber, at the Department of Farm Power and Machinery, Sylhet Agricultural University. It was placed under natural shade (protected from direct solar radiation) but was fully exposed to ambient temperature, relative humidity, and natural wind/airflow, without any additional structural enclosure or wind protection. Refrigerator temperature (3°C) reflected a standard commercial refrigerator setting, broadly within the low-temperature range ($4-7^{\circ}\text{C}$) reported as effective for green chilli storage in prior literature (Kapoor *et al.*, 2022); relative humidity inside the refrigerator was not measured during the trial. Weight loss percentage was calculated as the ratio of mass lost to the initial fresh mass, expressed as a percentage. Visual quality assessment (colour, firmness, and surface integrity) was conducted each day using photographic documentation. No formal numerical scoring scale was applied; colour, firmness, and surface integrity were assessed descriptively through direct visual observation, and daily photographs were used to record produce conditions and enable visual comparison across treatments and over time, rather than for quantitative scoring. Because firmness cannot be directly observed visually, it was inferred from specific proxy indicators visible in the daily photographs: surface wrinkling or shrivelling of the pod skin (indicating loss of turgor pressure) and visible changes in pod shape, rigidity, or drooping (indicating softening). Colour was assessed directly by observing the degree of green retention versus yellowing, and surface integrity was assessed by the presence or absence of visible microbial growth, pitting, or mechanical damage.

Economic Analysis

The economic analysis quantified the total construction cost of the evaporative cooling chamber based on material procurement costs

at prevailing local market rates in Sylhet, Bangladesh (year 2020). Cost items included all construction materials (sand bricks, river-bed sand, black PVC piping, cement, and straw cover) and labour, with unit prices recorded from local suppliers at the time of construction. As the structure has no moving parts, requires no electricity, and uses minimal consumable inputs during operation, cash maintenance costs for the durable brick-and-sand structure itself were assumed to be negligible after initial construction; however, the straw roof cover requires approximately annual replacement, and the ongoing operation requires daily water input and associated farmer labour costs were considered. Based on the expected durability of the brick-and-sand structure, we assumed a conservative service life of 5 years for per-unit cost estimation.

Statistical Analysis

Each treatment (evaporative cooling chamber, ambient open-air control, and refrigerator) was conducted as a single trial without independent replication (see Experimental Procedure and Performance Evaluation); therefore, formal inferential statistics comparing treatments (e.g., ANOVA) were not applicable. When repeated daily measurements within a trial allowed meaningful summary statistics, we calculated descriptive statistics (mean $\pm$ standard deviation, minimum, maximum, and range) using Microsoft Excel. Because weight loss is cumulative, sequential daily values within a trial are not independent observations; formal inferential hypothesis testing (e.g., paired t-tests) was therefore not considered appropriate or valid for these data, and no significance claims are made. Weight loss, temperature, relative humidity, and qualitative visual assessment data are instead reported descriptively, as mean $\pm$ SD, minimum, maximum, and range where applicable, and compared qualitatively across treatments.

Results

As each treatment (evaporative cooling chamber, ambient control, and refrigerator) was

conducted as a single trial without independent replication (see Materials and Methods), the results below are presented descriptively and comparatively; where repeated daily measurements within a trial permit meaningful summary statistic (e.g., weight loss), these are reported with appropriate caveats regarding the non-independence of sequential daily observations.

Thermal Performance Under No-Load Conditions

During the no-load trial (9-16 November 2020), the ambient dry-bulb temperature ranged from 24°C to 32°C, with midday peaks consistently exceeding 28°C. The inside chamber temperature ranged from 18°C to 24°C during the observation period. The maximum temperature drop recorded was 10°C, observed on two occasions: at midday (12:50) on 14 November 2020, when the ambient temperature reached 32°C, and in the morning (09:00) on 13 November 2020, when the ambient temperature was 28°C (Table 1). Table 1 summarises the average daily temperatures and relative humidity under no-load conditions.

Across the 8-day no-load trial (24 measurements), ambient dry-bulb temperature averaged $27.3^{\circ}\text{C} \pm 2.3^{\circ}\text{C}$ (range: 24-32°C) compared with $22.0^{\circ}\text{C} \pm 1.3^{\circ}\text{C}$ (range: 18-24°C) inside the chamber, while ambient relative humidity averaged $74.6\% \pm 9.6\%$ (range: 52-90%) compared with $83.6\% \pm 6.9\%$ (range: 70-93%) inside the chamber. The temperature differential was smallest in the early morning (09:00) when ambient relative humidity was highest (68-87%), and largest at midday when ambient humidity was lowest (52-76%). Dadhich, Dadhich, and Verma (2008) found that relative humidity inside was 80% to 87%, while it was 45-60% outside. In this research, inside relative humidity was consistently higher than ambient, ranging from 70% to 93%, with an average of approximately 84% well within the optimal range (80-95%) recommended for short-term storage of green chilli (Hameed *et al.*, 2013). The saturation efficiency calculated by Equation 1 varied considerably with ambient conditions. The calculated saturation efficiency frequently

exceeded the theoretical maximum of 100%, a physically implausible result indicating that at least one of the paired temperature readings used in each calculation was unreliable. As the two uncalibrated thermometers were never cross-calibrated against a common reference, we cannot rule out a systematic offset between them; however, this same uncertainty also affects the reliability of the absolute temperature-drop values reported from these

instruments, not only the derived efficiency metric. We therefore do not treat the reported temperature drop and efficiency figures as precisely validated measurements; they are presented as indicative of the general cooling trend observed, and should be interpreted with appropriate caution pending verification with calibrated, cross-referenced instrumentation in future work.

Table 1- Temperature and relative humidity measurements (at 09:00, 12:50, and 16:00) without keeping products under no-load conditions

Experiment		Outside temperature		RH	Chamber temperature		RH	Temperature drop
Date	Time	DBT	Tw		DBT	Tw		
09-11-20	9:00	26	24	87	24	22	87	2
	12:50	27	23.5	76	24	22.5	89	3
	16:00	25	24	90	23	23	92	2
10-11-20	9:00	24	22	87	23	22	90	1
	12:50	25	23	76	23	22	91	2
	16:00	25	23	87	22	21	93	3
11-11-20	9:00	24	21.5	81	23	21.5	89	1
	12:50	25	22	76	23	21	86	2
	16:00	24	22	86	22	21	91	2
12-11-20	9:00	27	22.5	68	21	19	81	6
	12:50	29	24.5	69	20	19	74	9
	16:00	25	23	84	22	21	90	3
13-11-20	9:00	28	24.5	75	18	18.5	80	10
	12:50	30	24	65	22	18.5	74	8
	16:00	28	25	79	22	20.5	87	6
14-11-20	9:00	28	24.5	75	22	19.5	79	6
	12:50	32	25.5	60	22	17	72	10
	16:00	29	24	66	21	20	87	8
15-11-20	9:00	28	24.5	75	21	18.5	80	7
	12:50	30	25	66	21	18	76	9
	16:00	29	24	67	23	21.5	87	6
16-11-20	9:00	28	24.5	76	21	19	82	7
	12:50	31	20	52	22	18	70	9
	16:00	29	25	67	23	21.5	80	9

Thermal Performance During Green Chilli Storage (Load Condition)

During the 10-day storage trial (17-26 November 2020), the ambient dry-bulb temperature ranged from 20°C to 33°C, with the maximum recorded at midday on 25 and 26 November (33°C). The inside chamber temperature was consistently lower than the ambient, ranging from 17°C to 24°C. The lowest recorded inside temperature was 17°C and the highest was 24°C. The maximum temperature drop under load conditions was 10°C (Table 2).

The average inside temperature over the storage period was 21.1°C, and the average inside relative humidity was 80.1%. The inside chamber's cooling efficiency during the load phase ranged from approximately 57% to 125%, with values exceeding the theoretical maximum of 100% in a subset of readings, consistent with the instrument reliability concerns noted for the no-load phase. As discussed above, this uncertainty affects the reliability of the absolute temperature drop values as well as the derived efficiency metric, and both are reported as indicative rather than

precisely validated figures. As with the no-load results, the directly observed temperature drop (up to 10°C) and relative humidity increase are reported as the primary, though not fully

validated, performance indicators, and saturation efficiency values for the load phase should likewise be interpreted with caution.

Table 2- Temperature, relative humidity, and temperature drops in the chamber keeping green chilli (load condition)

Experiment		Ambient Temperature		Relative Humidity	Storage Temperature		Relative Humidity	Temperature drop
Date	Time	DBT	Tw	RH%	DBT	Tw	RH%	
17-11-20	9:00	26	22.5	76	24	21.5	81	2
	12:50	32	24	51	23	17	68	9
	16:00	26	23.5	81	24	20	92	2
18-11-20	9:00	24	19.3	65	21	19	82	3
	12:50	30	21.5	47	22	18.5	72	8
	16:00	25	20.4	66	21	19.5	87	4
19-11-20	9:00	23	18.5	66	20	18	83	3
	12:50	30	21	46	21	17.5	72	9
	16:00	26	22.2	72	23	20	82	3
20-11-20	9:00	24	20	71	19	17	82	5
	12:50	30	21	47	22	18	71	8
	16:00	26	22	73	23	20.5	81	3
21-11-20	9:00	23	20.5	75	21	18.5	79	2
	12:50	29	21	50	20	17	75	9
	16:00	25	21	72	20	18	81	5
22-11-20	9:00	23	19.8	75	20	18	82	3
	12:50	29	21	48	20	17	74	9
	16:00	26	22.5	74	23	21	85	3
23-11-20	9:00	20	16.5	70	18	16	83	2
	12:50	30	22	49	24	17	75	6
	16:00	26	21.8	70	21	19.5	87	5
24-11-20	9:00	23	19	69	19	17	84	4
	12:50	31	22.5	48	23	17	76	8
	16:00	24	20	70	20	18.5	92	4
25-11-20	9:00	24	19	67	18	16	80	6
	12:50	33	23	45	23	16	80	10
	16:00	25	20.5	70	20	18	76	5
26-11-20	9:00	24	17.3	70	17	15	81	7
	12:50	33	23.5	45	24	14.5	79	9
	16:00	25	20.7	76	20	16.5	81	5

Physiological Weight Loss

Table 3 presents the cumulative percentage weight loss of green chilli under the three storage treatments over 10 days. Under ambient storage, weight loss increased rapidly, reaching 35.4% by Day 10, with visible wilting and colour changes apparent from Day 5 onwards. Inside the evaporative cooling chamber, weight loss was substantially lower, reaching a cumulative 12.4% on Day 10, consistent with values reported for other evaporative coolers used to store horticultural produce (Mogaji & Fapetu, 2011). The refrigerator at 3°C achieved

the lowest cumulative weight loss of 8.5% on Day 10. Weight loss over the 10-day trial differed markedly among treatments (ambient: 21.4% ± 13.5%; EC chamber: 7.3% ± 4.2%; refrigerator: 3.0% ± 2.7%; mean ± SD, descriptive statistics only). Because each treatment was a single, unreplicated trial and weight loss is cumulative over time, these daily values are not independent observations; we therefore report this comparison descriptively and do not apply inferential hypothesis testing or significance claims (e.g., p-values) to these data. Yeneneh and Walle (2024) mentioned that

the integrated system achieves approximately 90% relative humidity levels and reduces the

temperature inside the storage by 10°C below the ambient temperature.

Table 3- Cumulative percentage weight loss of green chilli (*Capsicum annuum* L.) under three storage conditions over 10 days

Day	1	2	3	4	5	6	7	8	9	10
Ambient (%)	2.4	5.0	9.0	11.4	19.0	29.0	33.4	34.3	34.9	35.4
Chamber (%)	1.3	3.2	3.6	4.5	5.2	9.0	10.8	11.2	11.8	12.4
Refrigerator (%)	0.4	1.0	1.2	1.5	1.6	2.0	2.4	3.8	7.1	8.5

Post-Harvest Quality Assessment

Green chilli stored in the evaporative cooling chamber showed no visible loss of firmness, based on qualitative visual assessment, and retained green colour throughout the 10-day trial. No significant surface wrinkling, yellowing, or microbial spoilage was observed up to Day 10. Chillies stored under ambient conditions lost turgor pressure visibly by Day 3 and exhibited widespread yellowing and softening by Day 5. Those stored in the refrigerator maintained firmness and colour comparable to the

chamber, though slight surface condensation was observed upon removal from the cold storage. So, visible firmness loss was found to be greater under ambient storage compared with the cold storage and refrigerator treatments. The fungal attack was also noticeable on the green chilli bodies that were stored in the ambient area.

The firmness of the green chilli decreased more in the ambient section compared to the cold storage and the refrigerator. A comparative analysis of the firmness of the stored green chillies is shown in Figure 2.



Fig. 2. Pictures of green chilli (a) on the first day at ambient temperature, (b) on the first day in cooled storage, (c) on the first day in the refrigerator, (d) after ten days at ambient temperature, (e) after ten days in cooled storage, and (f) after ten days in the refrigerator

Cost analysis of developed Evaporative cooling storage structure

The total estimated construction cost of the

evaporative cooling chamber was 6,800 Tk for the first year (Table 4). This cost encompasses

all materials including sand bricks, river-bed sand, PVC piping, cement, straw cover, and labour. After the first year, no recurring operational or maintenance costs are anticipated, rendering the per-unit cost negligible over a 5-year service life. Water costs were negligible, as the system relied on manually filled tube-well water rather than a metered supply, and no maintenance costs were incurred during the trial period. Based on the assumed 5-year service life, the annualised (depreciated) cost is approximately 1,360 Tk per year. As this analysis reflects 2020 local market prices (the year of construction), and construction material costs in Bangladesh have risen substantially since then due to inflation and currency devaluation, the reported cost should be interpreted as a 2020 baseline; a rough inflation-adjusted estimate suggests a present-day cost of approximately 9,500-10,000 Tk. This estimate assumes the chamber is built on land the farmer already has, so no land cost is included. Straw roofing wears out with weather exposure and would likely need

replacing about once a year (100 Tk each time); over 5 years, that adds roughly 400 Tk, bringing the annualised cost to about 1,440 Tk/year (1,360 Tk depreciation plus 80 Tk/year for straw). Water costs stay negligible, since the source is an unmetered tube well. Operating labour was not included as a cash cost in this analysis, as manually refilling the 90 L reservoir three times each day (estimated at approximately 15-20 minutes of farmer time per day, based on typical manual water carrying rates) is assumed to represent unpaid family labour integrated into routine farm activities, consistent with common practice in smallholder cost analyses; however, we note this time commitment explicitly here as a real, non-trivial operational input (approximately 2.5-3.3 hours per 10-day storage cycle) that should be considered when assessing practical adoption feasibility, and which would represent an implied labour cost of approximately 150-200 Tk per cycle, if valued at typical local agricultural wage rates.

Table 4- Estimated construction cost of the evaporative cooling chamber (BDT, 2020)

Materials	Quantity	Unit Price (Tk)	Total (Tk)
Sand bricks	360 pcs	10.00	3,600
River bed sand (fine)	4.5m	100	450
Black PVC pipe	5 m	50.00	250
Bucket	1	200	200
Tap	1	50	50
Cement	2 bags (each bag 50 kg)	450.00	900
Jute Bag	5	30.00	150
Bamboo	4	200	600
Straw			100
Labour	1	500	500
Total			6,800

Discussion

The zero-energy evaporative cooling chamber evaluated in this study demonstrated a consistent capacity to reduce storage temperature by 2-10°C relative to ambient conditions and to maintain the inside relative humidity at 68-92%. These thermal characteristics substantially retarded the physiological deterioration of green chilli, reducing ten-day weight loss from 35.4% under ambient conditions to 12.4% inside the chamber.

The highest temperature drops (8-10°C) were consistently recorded at midday when the ambient wet-bulb depression was greatest. This behaviour is thermodynamically expected and is consistent with the theoretical framework of [Chopra et al. \(2022\)](#), who demonstrated that an evaporative cooling benefit is greatest during periods (year-round over a period of 5 years) of high dry-bulb temperature and low relative humidity.

The average inside temperature of 21.1°C and average relative humidity of 80.1%

achieved during the load trial are within the acceptable range for short-term green chilli storage. Kapoor *et al.* (2022) reported that cold storage at 4-7°C extends shelf life by several weeks, whereas ambient storage at 25-30°C results in rapid quality loss. The visually assessed firmness retention over the 10 days is broadly consistent with shelf-life extensions reported for evaporative cooling systems applied to other fresh vegetables (Mogaji & Fapetu, 2011), though direct comparison is limited by differences in crop type and system design between studies. The substantially lower weight loss observed in the chamber (12.4%) relative to ambient storage (35.4%) can be explained by the higher relative humidity maintained inside the chamber (80.1% versus ambient levels frequently below 70%), which reduces the vapour pressure deficit between the produce surface and surrounding air, thereby slowing transpiration water loss. The lower chamber temperature likely also reduced the respiration rate of the stored chillies, slowing metabolic degradation and associated colour and firmness changes. These findings are broadly consistent with Piloo and Vida (2014), who reported that an evaporative cool chamber in Pasighat, India, maintaining 20.4-30.2°C and 74-95% RH (versus ambient 26.1-31.8°C and 59-79% RH), extended green chilli shelf life to 8-10 days compared with only 4-5 days under ambient storage—a similar direction and magnitude of improvement to that observed in the present study, despite differences in absolute temperature and humidity ranges between the two locations.

Defraeye *et al.* (2023) cautioned that unsatisfactory evaporative cooler performance, especially in humid periods, is a principal barrier to farmer adoption. The present study was conducted in November, when Bangladesh experiences its driest months with relative humidity frequently falling below 70% at midday. Deployment of this technology during the monsoon season (June-September), when ambient relative humidity regularly exceeds 80-90%, would likely yield substantially reduced cooling benefits. As evaporative cooling performance is fundamentally governed by the

wet-bulb depression, which is largest under precisely the hot, dry conditions characteristic of November, the temperature drop, humidity increase, and weight-loss reduction reported in this study should be interpreted as representing near-optimal, best-case performance for this technology rather than typical performance across the full annual cycle. Performance during other months, and particularly during the humid monsoon season, would be expected to be substantially lower, and this limits the generalisability of the reported results beyond the specific seasonal window tested. The findings therefore tentatively suggest that targeted seasonal use of the ZECC, aligned with the dry winter harvest flush of Rabi vegetables, may represent a favourable deployment window, pending confirmation across additional seasons. Beyond the construction cost itself, the economic value of the chamber can be illustrated by the loss prevented relative to ambient storage. Based on the observed reduction in weight loss (35.4% under ambient storage versus 12.4% in the chamber) and a local market price of approximately 80 Tk/kg for green chilli, the chamber's tested 10 kg capacity would retain approximately 2.3 kg more produce per the 10-day storage cycle relative to ambient storage, corresponding to a value of loss prevented by approximately 184 Tk per cycle. Assuming repeated use across the approximately 120 day dry winter season identified as the favourable deployment window (approximately 12 ten-day cycles), this corresponds to an estimated seasonal value of loss prevented of approximately 2,208 Tk. Against the one-time construction cost of 6,800 Tk (or the inflation-adjusted estimate of 9,500-10,000 Tk), this suggests a payback period of approximately 3-4 years of seasonal use, within the assumed 5-year service life of the structure, rather than within a single storage cycle. This estimate does not include the implied labour cost of daily reservoir refilling (approximately 150-200 Tk per cycle, as noted below), which would further extend the payback period if valued as a cash cost; it is also sensitive to actual farmer throughput, batch size, and market price fluctuations, and should be treated

as illustrative rather than a precise financial projection.

A limitation of the present study is that thermal and post-harvest quality performance were evaluated during a single 19-day window within the winter season (9-26 November 2020), rather than across the full Nov-Feb period. A further limitation concerns instrument reliability: as detailed in the Results section, saturation efficiency values during both the no-load and load phases occasionally exceeded the theoretical maximum of 100%, indicating that the two thermometers used for outside and inside measurements were not cross-calibrated against a common reference; this uncertainty affects confidence in the absolute temperature-drop values reported throughout this study, which should therefore be interpreted as indicative of the general cooling trend rather than precisely validated measurements. Nonetheless, because the chamber's brick-and-sand structure is durable and requires only minor recurring costs (periodic straw replacement and farmer labour for daily water refilling), the one-time construction investment (6,800 Tk) can be amortised over several years of repeated seasonal use, supporting economic feasibility even under seasonal deployment, with an estimated payback period of approximately 3-4 years. Future work should evaluate the system across multiple seasons, particularly during the hot and dry pre-monsoon period, to confirm performance across the full range of conditions farmers would encounter. In addition, the chamber's dimensions and discharge rate were selected based on established design precedent and practical construction constraints rather than a formal engineering calculation (e.g., psychrometric heat-and-mass balance); future studies should incorporate such calculations to optimise chamber design for specific storage capacities and climates. Additionally, relative humidity inside the refrigerator was not measured. Notably, refrigerator weight loss accelerated sharply between Day 8 and Day 9 (3.8% to 7.1%), consistent with delayed-onset chilling injury after a lag period, a pattern documented in cold-sensitive produce stored

below approximately 5-7°C; this suggests that chilling injury may have been developing despite the lack of earlier visible symptoms. As the refrigerator's 3°C setting is slightly below the 4-7°C range commonly reported as safe for green chilli storage, future studies should monitor refrigerator RH and assess chilling-injury risk more systematically. Furthermore, visual quality assessment relied on descriptive observation rather than a standardised scoring scale; future studies should incorporate a formal rating system (e.g., a defect-severity or hedonic scale) to improve the objectivity and reproducibility of quality comparisons.

Conclusion

A zero-energy evaporative cooling chamber constructed from locally available sand bricks and river-bed sand reduced the storage temperature of green chilli by up to 10°C relative to ambient conditions, maintained the inside relative humidity at an average of 80.1%, and limited physiological weight loss to 12.4% over a 10-day storage period (noting the instrument-related caveats on temperature-drop precision discussed above). Green chilli firmness, as judged by visual assessment, was well preserved throughout the trial. The total construction cost of 6,800 Tk, with only minor recurring costs (periodic straw replacement and farmer labour for water refilling), renders this technology economically accessible to smallholder farmers in Bangladesh and comparable developing-country contexts. The evaporative cooling chamber achieved a maximum temperature drop of 10°C at midday under both no-load and load conditions, demonstrating that the presence of stored produce does not compromise the thermal performance of the system. Inside temperature (mean: 21.1°C) and relative humidity (mean: 80.1%) were within the acceptable range for short-term post-harvest preservation of green chilli. Physiological weight loss in the chamber (12.4%) was substantially lower than ambient storage (35.4%) and approached refrigerator storage (8.5%), confirming the system's practical utility as an intermediate-cost storage option. The technology is technically simple,

requires no electricity, uses locally available materials, and is amenable to construction by farmers without specialised skills. Given its low cost and simple construction, this technology may be a suitable candidate for promotion through agricultural extension programmes or farmer cooperative training schemes; however, broader adoption would benefit from further validation across multiple seasons and locations before wider dissemination is recommended.

Author Contributions

Al-Arman Oyon: Methodology, Data acquisition, Data pre- and post-processing, Text mining, Visualisation, Conceptualisation, Review and editing services

Md Mahfuzul Hasan: Visualisation, Technical advice, Review and editing services

Md. Fuad Ahmed: Methodology, Data acquisition, Review and editing services, Validation

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ارزیابی عملکرد و جنبه‌های اقتصادی یک محفظه سرمایش تبخیری با مصرف انرژی صفر برای نگهداری فلفل سبز پس از برداشت

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چکیده

ضایعات پس از برداشت فلفل سبز (*Capsicum annuum* L.) به دلیل فقدان زیرساخت‌های مقرون به صرفه برای سردخانه‌ها، همچنان مشکلی اساسی برای کشاورزان خرده‌پا در بنگلادش محسوب می‌شود. در این پژوهش، یک محفظه سرمایش تبخیری با مصرف انرژی صفر طراحی و اجرا شده و عملکرد آن مورد ارزیابی قرار گرفت؛ این محفظه با استفاده از آجرهای ماسه‌ای موجود در محل و ماسه بستر رودخانه (به عنوان واسط سرمایش) ساخته شد. این سازه (با ابعاد ۱۵۵ × ۶۳ × ۸۰ سانتی‌متر) بر اساس اصول سرمایش تبخیری (EC) و بدون نیاز به هیچ گونه انرژی الکتریکی کار می‌کرد. در شرایط بدون بار (خالی)، محفظه در میانه روز به حداکثر کاهش دمای ۱۰ درجه سانتی‌گراد دست یافت. طی یک دوره آزمایشی ۱۰ روزه برای نگهداری فلفل سبز، میانگین دمای داخلی محفظه ۲۱/۱ درجه سانتی‌گراد و میانگین رطوبت نسبی آن ۸۰/۱ درصد بود؛ این در حالی است که شرایط محیطی شامل دمای ۲۰ تا ۳۳ درجه سانتی‌گراد و رطوبت نسبی ۴۵ تا ۸۱ درصد بود. میزان کاهش وزن فیزیولوژیک داخل محفظه پس از ده روز تنها به ۱۲/۴ درصد رسید که به طور قابل توجهی کمتر از مقدار ۳۵/۴ درصد تیمار شاهد در شرایط محیطی بود و با مقدار ۸/۵ درصد ثبت شده در یخچال (با دمای ۳ درجه سانتی‌گراد) قابل مقایسه بود. سفتی فلفل که به صورت کیفی و از طریق مشاهدات بصری و عکاسی ارزیابی شد، در طول دوره ۱۰ روزه در شرایط نگهداری با سیستم EC به مراتب بهتر از شرایط محیطی حفظ گردید. کل هزینه ساخت برای سال اول ۶۸۰۰ تاکا (واحد پول بنگلادش) برآورد شد و هزینه‌های جاری آن تنها شامل موارد جزئی نظیر تعمیر و نگهداری سالانه سقف و نیروی کار روزانه برای بهره‌برداری بود. این فناوری گزینه‌ای امیدوارکننده و کم هزینه برای نگهداری محصولات پس از برداشت توسط کشاورزان خرده‌پا در مناطق گرمسیری به شمار می‌رود، هرچند انجام ارزیابی‌های بیشتر در فصول و مکان‌های مختلف ضروری است.

واژه‌های کلیدی: رطوبت، سفتی، فناوری کم هزینه، کاهش ضایعات، کیفیت نگهداری

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