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Implementation and Performance Evaluation of a Community-Scale Adobe Evaporative Cooling Chamber for Vegetable Preservation

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Abstract: The construction of evaporative coolers in remote areas can increase the longevity of vegetables, improving food security and the local economy of small farmers in remote, impoverished communities without access to electricity. This work presents a 1:1 scale prototype of an 8 m^3 (2.1 × 2.1 × 2.3 m) stabilized adobe evaporative cooler, with a design based on the appropriate technology framework, and it was built as a chamber using double adobe walls, filled with wet sand, to induce evaporative cooling. Furthermore, the paper presents the prototype's performance evaluation. The tests were carried out in the dry and wet states, with different volumes of water. The results show good performance compared with other prototypes, although the optimum watering volume could not be determined because of the high climate variance (outside temperature and humidity) that prevented the repetition of the experiments in identical operating conditions. Stabilized adobe proved to be a good choice for use in the cooler, even when subject to moisture accumulation, indicating an estimated long lifetime for the cooler. The data obtained about the efficiency of evaporative cooling show that the cooler, as expected, has its best performance on the hottest and driest days, reducing the internal temperature (up to 13.24 °C) and managing to keep the internal humidity. The cost, efficiency, durability, and replicability make the proposed evaporative cooler a feasible solution for food preservation.

Keywords: zero energy; food security; vegetable conservation; cooling; evaporation; zero hunger; technology; post-harvest facility; remote communities

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Citation: Davalo, K.M.; Yuba, A.N.; Pinto, J.O.P. Implementation and Performance Evaluation of a Community-Scale Adobe Evaporative Cooling Chamber for Vegetable Preservation. *Buildings* **2023**, *13*, 1401. https://doi.org/10.3390/buildings13061401

Academic Editors: Michael A. Lacasse, Hua Ge and Liangzhu Wang

Received: 3 April 2023
Revised: 16 May 2023
Accepted: 24 May 2023
Published: 29 May 2023

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1. Introduction

The estimated global population growth tends to put pressure on food production worldwide. This production is supposed to increase by 60% by 2050, compared to the 2005–2007 period; however, a large amount of food is lost and wasted. While most of the waste (at the end of the chain) occurs in developed countries, the losses (at crop management and post-harvest stages) are more common in developing countries—Accounting for as much as 28% in Latin America according to FAO. With global food loss estimated to be a third of production, or 1.8 billion tons [1,2] per year, prioritizing loss prevention along the production chain will become an increasingly necessary and productive industry.

It has been reported that, in East Asia, food waste ranges from 10% to 50%, and in Africa, it reaches up to 80% [3]. In India, in one year, losses range from 30% to 35% and occur in the harvesting, storage, classification, transport, packaging, and distribution phases, with only 2% becoming value-added products [4]. In Zimbabwe, it was reported that the losses of sweet potatoes could reach 60% of post-harvested production [5]. In turn, in Bangladesh, the post-harvest loss rate of tomatoes and eggplant is 26%, while the average daily consumption of fruits and vegetables is one-third of the FAO recommendation [6].

Considering the importance of the use of green energy for African countries [7], as well as for other developing countries, and increase the use of such green energy in direct energy transformation (solar to heat, for instance) resulting and lower investment and higher efficiency, among several ways of combating food loss recommended by the FAO, evaporative coolers (EC), also called cooler chambers, stand out as one of the mitigation factors due to their simplicity and low cost. They are one of the oldest methods of food preservation and work through a thermo-dynamic process of air called adiabatic saturation [8], consisting of food storage spaces that are cooled by the circulation of moist air, which can occur directly (wet wrap), indirectly (receives cooled air) or both, and depends on a hot and dry climate so that there is water evaporation [8]. These devices can decrease rapid food deterioration, allowing it to be consumed or sold for a longer period.

Researchers from Central Food Technological Research Institute (CFTRI), India, developed a metallic direct EC to compare its performance with a similar size indirect EC created by Habibunnisa et al. Both types reduced physiological losses, increasing the shelf life of fruits [9].

A ceramic pot inside another ceramic pot, filled with wet sand and a lid, is an indirect EC. With the same principle, S. K. Roy and partners initiated the Zero Energy Cool Chamber—ZECC series, at Indian Agricultural Research Institute (IARI), India, during the 1980s [10]. This model is ceramic, double-walled brick on a foundation also made of ceramic bricks. The cavity between walls is filled with sand to serve as a wet pad. A lid made of timber/bamboo culms and straw is built to cover the box to keep the air inside cool and humid. The ZECC became the main reference of much contemporary research related to ECs. The 1982 model lowered temperature (inner: 23–26.5 °C and ambient: 24.2–39.1 °C) and increased humidity (inner: 94–97% and ambient 9–36%) during the summer [4]. The subsequent works and models that were developed by the same authors and others showed similar behavior: humidity rise (more than 90%) and temperature fall (10–15 °C) compared to the ambient condition by watering the EC twice or three times a day. Many studies reported a prolonged shelf life of days or even for a few months, but the most frequent outcome is an increased shelf life of 1 or 2 weeks, making the EC suitable for short-term vegetable storage [4,6,11–16].

The indicators usually used to measure the performance of an EC include physiological weight loss, color preservation, firmness, extended shelf life, decay incidence, visual quality, and nutritious parameters [14,15,17,18]. For no-load tests, the main indicators for performance evaluation include temperature, humidity, and saturation efficiency [19]. The saturation efficiency, in turn, depends upon the shape and materials of the EC and the weather (inlet air temperature, relative humidity, air movement). A study of four materials in three different shapes of ECs determined a saturation efficiency between 89 and 91% [8]. A study reported a drop in temperature of 20 °C temperature under specific conditions, near 23.5 °C (wet bulb temperature), very close to maximum efficiency [20].

ECs are a particularly suitable option for farmers and communities in dry, hot, and remote locations of the developing world, where widespread use of electrical coolers, based as they are upon the compression and expansion cycle of an active refrigerant, is made impossible by the scarcity, or the absence, of a reliable power source. Hence, the opportunity to produce ECs with free, local materials and to substitute industrialized materials for a labor-intensive artisanal process should be given serious consideration. This would add other indicators to evaluate the success/ability of an EC to attend to the circumstances, such as water requirement, cost, storage volume capacity, free local materials content, and durability. Water, needed daily for proper functioning, is a special requirement that must be readily available.

This paper proposes a walk-in size indirect evaporative cooler for post-harvesting preservation of community-scale horticultural farm production. Its design is based on the use of local materials and local construction techniques aiming for low environmental impact and low cost. Next, a brief overview of cooler chambers, their operation principles, and performance indicators are presented. In sequence are shown the design and

implementation of a full-scale unit, the analysis of its results, and performance evaluation, followed by concluding remarks.

2. The Evaporative Cooler: Working Principle and Construction Material

2.1. Working Principle

Figure 1 shows a simplified diagram of an evaporative cooler consisting of two main parts: a food storage area (1) and an envelope called a wet pad (2). The food storage area has no specific requirement aside from the capacity to properly store the food. The pad, in turn, must be made of porous material able to retain water and through which air can flow easily. Materials such as charcoal, sand, clay, and natural or artificial fibers are among the most commonly used. When the pad is exposed to favorable climatic conditions, the hot and dry air passes through it, and the embedded water evaporates, generating cold air and humidity (3). Therefore, the pad must be irrigated to work properly. It requires 2260 kJ of energy to evaporate 1 kg of water; therefore, this is the amount of energy turned into cold air in the process [13,21]. In Figure 1, the dotted lines represent airflow; the red segment represents hot air, and the blue represents cold.

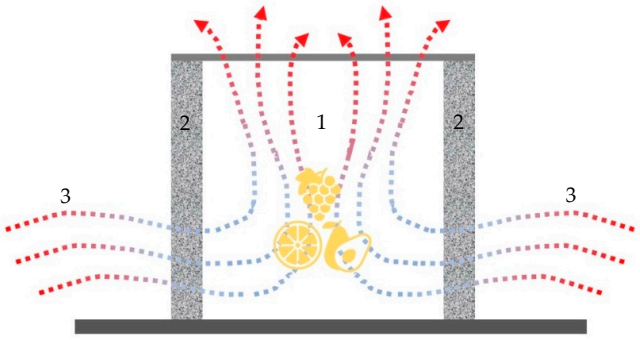


Figure 1. Simplified cross-sectional diagram of the evaporative cooler.

The coexistence of high temperature, low humidity, and the availability of water and wind are the key components for the optimal performance of evaporative coolers. They can function in different climatic conditions; however, cooler chamber models must be properly adapted to the conditions of its target environment [4].

Evaporative coolers may vary with regard to the type of system, storage volume capacity, shape, and construction materials (Figure 2).

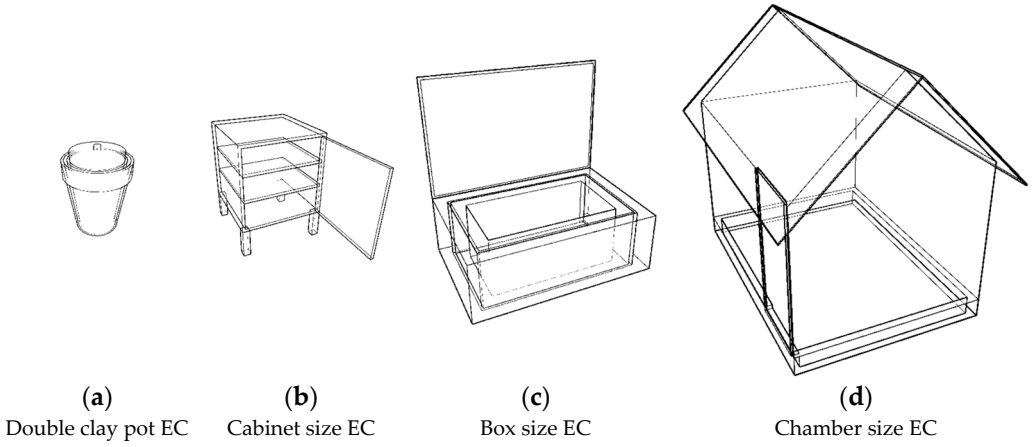


Figure 2. Comparative sizes of evaporative coolers shapes.

Figure 2a,b shows portable ECs. The double clay pot filled with sand (Figure 2a) is of the utensil size type suitable for volumes of up to 150 L [21]. The cabinet-size-type

evaporative cooler (Figure 2b) developed by Habibunnisa et al. is an indirect EC because it is made with metal sheet walls and a door, with a tray above, in contact with a damp piece of cloth kept moist by gravity. Below the cabinet, there is another tray to collect surplus water. The substitution of the opaque metallic walls for wire mesh makes it a direct EC. Although both had similar temperature performance, the indirect version had less physiological loss than the direct type. The relative humidity was lower in the direct version due to air movement [4,9].

A box-size-type is larger (Figure 2c) and adequate for 500–5000 L of vegetables [22]. The ZECC, mentioned above, is an evolutionary model used by many researchers. The structure requires construction in a shaded area. Baskets or plastic crates are used for the internal arrangement of vegetables. Watering depends on weather conditions but varies from 1 to 3 times a day [3]. The performance of this type of cooler in a field test, based on two models (100 and 200 kg), showed [10]:

- spoilage losses: the results, as expressed in terms of loss of product and loss of weight, in general, was approximately halved;
- increase in market value, varying according to the product;
- storage for 5 to 6 days without apparent spoilage;
- cost: \$100/100 kg (for 5 plastic crates) and \$813/200 kg (for 10 plastic crates, roof, and floor);
- payback time: 3 uses/100 kg and 8 uses/200 kg;
- performance: average daily variation between 26–33 °C and 29–28% humidity (before) to 22–27 °C and 62–56% humidity (after).

A bigger size of ZECC (50 crates, 1000 kg) was built by Roy (2009). The authors comment that the cost of this system is high (\$1000), but it is proportional to the cost of the 100 kg EC, i.e., \$1/kg. The payback time is 8 uses, similar to the 200 kg model [10].

Between 2012 and 2015, researchers at Ehine University in Japan contributed to the scientific advancement of evaporative coolers for vegetable storage. The original, Roy's cooler model, was progressively studied in a controlled environment: a semi-underground version to benefit from the thermal inertia of the earth [23]; substitution of the external wall's bricks with porous rock plate to facilitate water evaporation [16,24]; use of a solar adsorption plate [24] and additional structures to enhance the evaporation, such as a chimney and a ceramic pot with water [16]. A dynamic, optimized technique using neural networks and genetic algorithms to control watering could decrease the temperature to 4–7 °C and allow for an extension of the shelf life of tomatoes from 7 to 16 days [23].

The chamber-size-type evaporative coolers (Figure 2d), also called Zero Energy Storage Structure—ZESS, which constitutes a built environment, are suitable for collective production.

An important aspect is that as it is a built environment, the space under the roof could be used for storage, and then, the occupied area could be reduced, which may decrease the roof cost as well.

The source and volume of water must be considered in these projects due to the scarcity or inaccessibility of water in dry regions. Daily water consumption was 100 L for a 1.28 m^3 EC, 2100 L for an EC sand store, and 325 L for a 2-ton EC [4].

This is an opportunity to develop solutions to reduce the amount of required water or for collective problem-solving to enhance efficiency, such as the use of the underground soil cooling effect [16,25] or the soil itself as a construction material.

2.2. Soil as a Construction Material

The material and shape of the chamber have been addressed, showing their effect on temperature drop and food preservation [6,11–14,17,18,23,26]. Experimental studies give ideas for materials [5,8,14,21,27–29], and some of them address issues of implementation.

In developing countries, mainly in remote areas, the difficulties increase, and it is necessary to facilitate the deployment using low-cost, abundant, and/or cost-free materials that are locally available and culturally accepted [28,30].

In Vala's review, most of the proposed ECs have brick walls, while some are made of metal or wood, with just one unit reportedly made of clay [19] on the very small scale of 0.6 × 0.52 × 0.85 m. Soil/clay is a great opportunity to build evaporative coolers [21,26,29,31] because of its hygroscopicity; it can be found everywhere, and is mostly free.

The physical properties of the soil naturally propagate the evaporation and saturation of water from the environment, even without the introduction of liquid water (rain or irrigation). Its most diverse compositions (grains of different sizes), when associated with construction techniques (adobe, cob, and others), preserve the pores and facilitate evaporation, contributing to the optimal performance of evaporative coolers.

The thickness of the earthen walls (the thinner, the more evaporation, and the thicker, the more inertia) and the solar orientation of the walls' faces (the more incident sun, the more evaporation) are relevant factors in projects that use this construction material [21].

The earthen wall's natural hygroscopicity helps keep the relative humidity within a suitable range, insufficient for microbial development but high enough for food health. It promotes water adsorption from the air at night due to the clay present in the composition, resulting in the evaporative cooling process even in the absence of watering.

Furthermore, the thermal inertia of earthen walls contributes to daytime cooling, as it causes the lag of the ambient temperature peak relative to external temperature and the damping of the internal temperature as long as there is no natural ventilation [21,32], working as a temperature filter. On the other hand, it can maintain a higher indoor temperature despite sudden drops in outdoor temperature or arid climate regions (of high contrast between daytime and nighttime outdoor temperatures).

3. Method

3.1. The Cerrado Cooler Chamber Design

Initiatives in underprivileged communities must, in general, have low implementation and maintenance costs, durability, and replicability. Among the technology frameworks that best adhere to these requirements is the so-called Appropriate Technology (AT), the principle of which is to blend local and external knowledge, resulting in a workforce-intensive solution that relies on local materials [30,33]. AT results in projects that are cheaper, easier to maintain, have a lower carbon footprint, and are replicable. The Cerrado Cooler Chamber (3C) was designed by Davalo [34] based on such a framework.

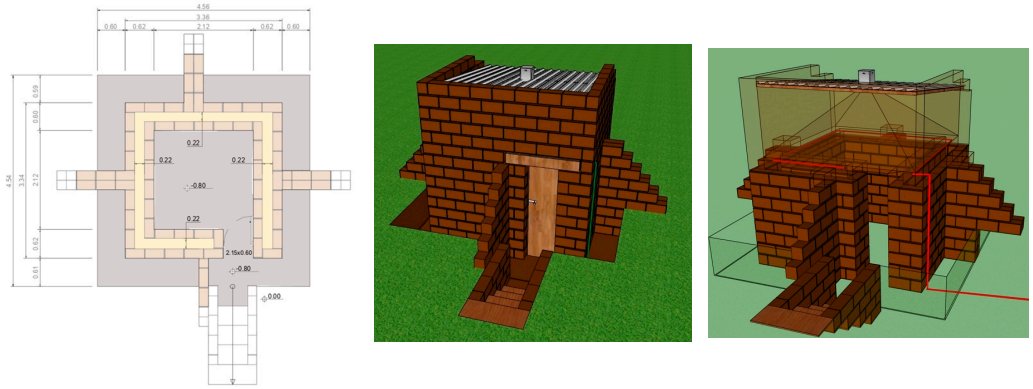
The 3C is a community-scale cooler chamber, and its prototype was built outdoors, full scale, at the campus of the Federal University of Mato Grosso do Sul, in a Brazilian region dominated by a biome called Cerrado, which is a tropical savanna present in eastern Brazil. It has a semi-humid tropical climate with two main seasons throughout the year: wet and dry. The temperature ranges from 22 and 27 °C, while the average precipitation ranges from 80 to 200 cm in almost all areas. Although the 3C was developed in Cerrado, whence its name, it was developed primarily for the sub-Saharan region. Since the sub-Saharan region is hotter and drier than Cerrado, the 3C is expected to perform better there.

As mentioned earlier, the 3C was developed using the TS framework and therefore sought to reach the following conditions [33,35,36]:

- to be a small-scale solution involving the culture and interests of the local population;
- to include locally available technology, focusing on a simple, robust, and adaptable solution that allows its usage without specific prior knowledge;
- to have a small ecological footprint;
- to be low-cost, labor-intensive, involve cooperative work, create local job opportunities, and contribute to the economic development of the local community;
- to be autonomous, decentralized, and open source;
- to be community-maintained after training members of the community to this end.

The 3C is an earth-based community-scale chamber conceived with the goal of achieving these conditions. It is a square chamber measuring 2.10 × 2.10 m and 2.20 m high for storage and conservation of up to 1100 kilos of fruit and vegetables (54 plastic crates). The system has four double walls of 20 × 20 × 40 cm adobe stabilized with cement (12 parts of

soil + 1 part of cement) in load-bearing masonry, filled with sand, totaling 60 cm thick, as shown in Figure 3. The soil must have at least 40% of clay content.



(**a**) (**b**) (**c**)

Figure 3. The Cerrado Cooler Chamber design: (**a**) floor plan; (**b**) perspective; (**c**) water dripping pipes.

The 3C was designed semi-buried to compare its performance with the unburied version. Initially, although semi-buried, the volume of soil around it was removed so that 3C could behave similarly to the unburied one. In the future, the soil volume will be replaced to evaluate the performance of the semi-buried 3C. In this work, only the performance of the unburied 3C is evaluated.

The operation of the 3C consists of water dripping onto the sand pad to keep it moist. The evaporation of water is made possible by the porosity of the adobe walls, allowing contact between hot and dry air and water, resulting in the cooling of the internal volume of the 3C. The water can be applied by (1) manually watering directly on the sand pad or (2) a hose and/or perforated pipes (Figure 3c). Adobe walls were chosen because of their thermal performance due to soil's hygroscopicity (the ability to capture, retain, and release water vapor) and because the water required for operation is a concern in remote and dry regions. Hence, even without dripping water, the cooler has performance advantages. The hot and humid air inside the 3C is expelled through the hood, whose top passes through the roof. The expelled air is then replaced by outside air, which enters the room through the opening below the door.

3.2. The Cerrado Cooler Chamber Construction and Instrumentation

Once the 3C was designed, its construction was carried out in 2019. First, around 1000 adobes were manually produced. Then the hole was excavated, compacted, and leveled. The double load-bearing masonry walls were then built, simulating the same production process and tools as can be accessed in remote areas. There are no steel bars, and all the bending forces (due to the moist sand in the middle) are compensated by the buttresses made with the same adobes. On the inside, the loads are supported by wooden planks. The roof was constructed with wooden logs and a sheet metal. A plastic hood was built under the roof, sustained by a PVC pipes pyramidal structure. The top is a reused can. The walls are left bare of plaster or painting. A wooden door with an opening was put in. It took about 60 days to be constructed by three people at an overall cost of 292 dollars, not including soil, tools, plastic crates, and water. That resulted in less than US$0.27 per kilogram, which is less than one-third of the average cost reported in the literature, which is about US$1.00 per kilogram [10,13]. Figure 4 shows the 3C construction phases.



(**a**) (**b**) (**c**)

Figure 4. 3C construction phases: (**a**) adobe production; (**b**) beginning of the construction; (**c**) front view.

To evaluate the 3C performance, its internal and external temperature and humidity data were gathered for different watering volumes. To measure the internal temperature and humidity, three sensors (Hobo (Onset) H08-003-02, which has ±5% accuracy, and one Data Logger Testo 175T2, which has an accuracy of ±0.2 °C were installed inside the 3C, in three different levels (a1: 0.0 m, a2: 2.2 m, and a3: 3.2 m). Figure 5 shows the sensors, data logger placement, and the water flow controller. Periodically, whenever the data logger memory storage was full, the data were downloaded and transferred to a personal computer. The outside temperature and humidity data were provided by the INPE—National Institute for Space Research, a Brazilian institute. The experiments were conducted with an empty 3C unloaded, i.e., without containing vegetables.

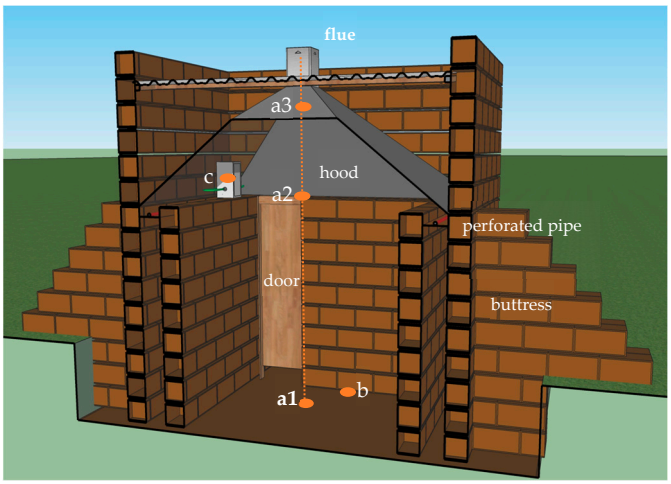


Figure 5. Instrumentation placement: (**a**) temperature and humidity sensors; (**b**) data logger; (**c**) water flow controller.

The performance of the 3C was evaluated using two methods: direct temperature gain and saturation efficiency. The first method is the difference between outside and inside temperatures, the most valuable information for the communities for indicating the expected temperature inside the cooler chamber, a detail crucial for food conservation. In its turn, the second is the ratio of inlet and outlet temperature difference and wet bulb depression, resulting in a maximal percentage of possible cooling relative to the outside temperature, and calculated using Equation (1) [37]:

$$\varepsilon = \frac{T_{e,db} - T_{l,db}}{T_{e,db} - T_{w,ub}} \quad (1)$$

where:

- $T_{e,db}$—dry bulb temperature of the air entering the cooler (°C);
- $T_{l,db}$—dry bulb temperature at the outlet of the cooler (°C);

- $T_{e,wb}$—wet bulb temperature at the inlet of the cooler (°C).

4. Results and Discussion

4.1. Temperature and Humidity Gains

For performance evaluation and to choose the optimal daily volume of water, the 3C was operated and monitored in 6 scenarios: 0, 40, 100, 200, 400, and 800 L/day watering cycles. These watering volume samples were defined to optimize water saving. In other words, the goal was to find the minimum volume of water that would result in the largest temperature gain. The strategy was to increase volume by small steps at the low end (0, 40, and 100), while at the high end, increase it by ones (200, 400, 800). So, if, out of all samples, the optimal watering volume measured on the high end, a new sample would be produced with the aim of discovering a superior watering volume. This process would interactively continue until water volume optimization had been reached. This strategy was inspired by a numerical optimization method called bisection. However, since, during the experiment, it was realized that the outside climate had high variance, preventing the repetition of the operating conditions, no conclusion could be drawn for optimization. Future work will be published with results on water volume optimization based on a mathematical model (simulation) of 3C, where the operating conditions can easily be repeated. Tables 1–6 and Figures 6–11 show the outside and inside temperatures and humidity. They show temperature and humidity gains in all scenarios.

Table 1. Experimental results for the no-watering scenario: inside, outside temperature and its difference; inside, outside humidity and its difference.

Time	T_{in} (°C)	T_{out} (°C)	DT (°C)	U_{in} (%)	U_{out} (%)	DU (%)
6:00	18.64	22.10	−3.46	80.80	51.00	29.80
8:00	19.02	24.10	−5.08	80.80	43.00	37.80
10:00	19.95	26.40	−6.45	80.70	39.00	41.70
12:00	20.69	28.60	−7.91	79.50	35.00	44.50
14:00	21.46	30.20	−8.74	79.50	35.00	44.50
16:00	21.46	28.90	−7.44	79.50	35.00	44.50
18:00	20.91	25.10	−4.19	80.70	50.00	30.70
20:00	20.73	22.60	−1.87	82.00	58.00	24.00
22:00	20.17	22.00	−1.83	82.00	59.00	23.00
0:00	19.79	21.30	−1.51	82.10	65.00	17.10
2:00	19.61	21.40	−1.79	82.10	64.00	18.10
4:00	19.59	21.60	−2.01	82.10	62.00	20.10
6:00	19.79	21.70	−1.91	82.10	54.00	28.10

Table 2. Experimental results for the 40 L/day scenario: inside, outside temperature and its difference; inside, outside humidity and its difference.

Time	T_{in} (°C)	T_{out} (°C)	DT (°C)	U_{in} (%)	U_{out} (%)	DU (%)
6:00	22.30	24.90	−2.60	55.50	32.00	23.50
8:00	22.99	30.80	−7.81	43.70	23.00	20.70
10:00	24.14	35.70	−11.56	34.20	16.00	18.20
12:00	25.25	36.80	−11.55	25.50	13.00	12.50
14:00	26.07	36.70	−10.63	25.40	13.00	12.40
16:00	26.42	33.00	−6.58	26.00	19.00	7.00
18:00	25.43	27.40	−1.97	42.30	38.00	4.30
20:00	24.90	24.30	0.60	47.80	52.00	−4.20
22:00	24.22	24.00	0.22	50.90	41.00	9.90
0:00	24.30	25.30	−1.00	48.20	36.00	12.20
2:00	24.22	25.10	−0.88	53.10	36.00	17.10
4:00	23.93	24.90	−0.97	50.70	38.00	12.70
6:00	23.69	24.80	−1.11	52.80	43.00	9.80

Table 3. Experimental results for the 100 L/day scenario: inside, outside temperature and its difference; inside, outside humidity and its difference.

Time	T_{in} (°C)	T_{out} (°C)	DT (°C)	U_{in} (%)	U_{out} (%)	DU (%)
6:00	22.67	24.10	−1.43	75.10	43.00	32.10
8:00	22.96	29.20	−6.24	53.80	31.00	22.80
10:00	24.01	33.70	−9.69	43.30	25.00	18.30
12:00	24.77	36.80	−12.03	32.50	18.00	14.50
14:00	25.54	37.00	−11.46	33.70	15.00	18.70
16:00	25.83	36.50	−10.67	30.90	14.00	16.90
18:00	25.03	31.60	−6.57	42.00	24.00	18.00
20:00	24.61	28.40	−3.79	47.90	30.00	17.90
22:00	24.38	26.80	−2.42	52.60	32.00	20.60
0:00	24.14	27.30	−3.16	57.70	30.00	27.70
2:00	24.03	27.10	−3.07	63.20	30.00	33.20
4:00	23.69	25.80	−2.11	69.10	33.00	36.10
6:00	23.46	27.10	−3.64	59.50	31.00	28.50

Table 4. Experimental results for the 200 L/day scenario: inside, outside temperature and its difference; inside, outside humidity and its difference.

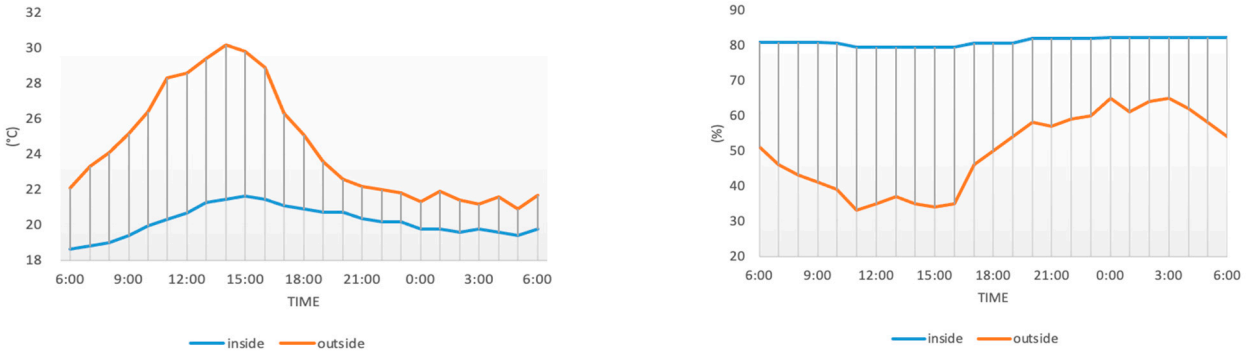
Time	T_{in} (°C)	T_{out} (°C)	DT (°C)	U_{in} (%)	U_{out} (%)	DU (%)
6:00	24.00	28.60	−4.60	65.60	38.00	27.60
8:00	25.16	36.20	−11.04	81.90	19.00	62.90
10:00	26.30	38.20	−11.90	74.90	13.00	61.90
12:00	26.88	39.40	−12.52	73.10	11.00	62.10
14:00	27.65	39.60	−11.95	67.70	11.00	56.70
16:00	27.46	37.00	−9.54	71.50	14.00	57.50
18:00	26.88	31.90	−5.02	74.90	22.00	52.90
20:00	26.32	27.00	−0.68	73.10	34.00	39.10
22:00	25.54	27.10	−1.56	67.90	33.00	34.90
0:00	25.16	25.10	0.06	66.40	45.00	21.40
2:00	24.97	26.00	−1.03	65.90	39.00	26.90
4:00	24.77	26.10	−1.33	64.60	36.00	28.60
6:00	24.77	31.30	−6.53	68.00	29.00	39.00

Table 5. Experimental results for the 400 L/day scenario: inside, outside temperature and its difference; inside, outside humidity and its difference.

Time	T_{in} (°C)	T_{out} (°C)	DT (°C)	U_{in} (%)	U_{out} (%)	DU (%)
6:00	24.77	26.00	−1.23	75.90	50.00	25.90
8:00	25.16	31.00	−5.84	78.00	34.00	44.00
10:00	26.12	34.30	−8.18	79.20	30.00	49.20
12:00	26.88	37.30	−10.42	79.10	25.00	54.10
14:00	27.46	37.60	−10.14	79.10	22.00	57.10
16:00	25.36	21.80	3.56	78.00	72.00	6.00
18:00	25.17	22.70	2.47	78.00	64.00	14.00
20:00	24.97	24.80	0.17	79.20	59.00	20.20
22:00	24.40	23.70	0.70	79.20	69.00	10.20
0:00	24.20	23.10	1.10	79.20	72.00	7.20
2:00	24.20	22.00	2.20	80.50	78.00	2.50
4:00	23.81	21.70	2.11	80.50	79.00	1.50
6:00	23.81	22.10	1.71	80.50	78.00	2.50

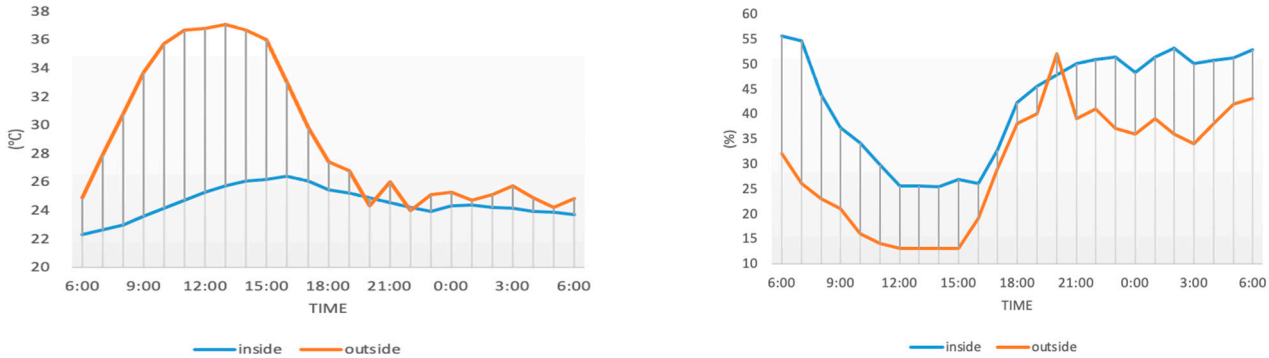
Table 6. Experimental results for the 800 L/day scenario: inside, outside temperature and its difference; inside, outside humidity and its difference.

Time	T_{in} (°C)	T_{out} (°C)	DT (°C)	U_{in} (%)	U_{out} (%)	DU (%)
6:00	22.26	25.60	−3.34	78.28	37.00	41.28
8:00	22.44	29.30	−6.86	78.96	32.00	46.96
10:00	23.39	34.10	−10.71	76.65	25.00	51.65
12:00	24.34	35.60	−11.26	73.81	24.00	49.81
14:00	24.92	35.30	−10.38	71.82	23.00	48.82
16:00	24.92	35.20	−10.28	70.88	25.00	45.88
18:00	24.55	30.90	−6.35	79.42	33.00	46.42
20:00	24.18	29.00	−4.82	81.46	37.00	44.46
22:00	23.79	27.50	−3.71	81.15	40.00	41.15
0:00	23.41	26.30	−2.89	80.42	41.00	39.42
2:00	23.03	25.50	−2.47	81.15	45.00	36.15
4:00	22.64	23.70	−1.06	82.30	51.00	31.30
6:00	22.64	26.10	−3.46	82.30	44.00	38.30



(**a**) (**b**)

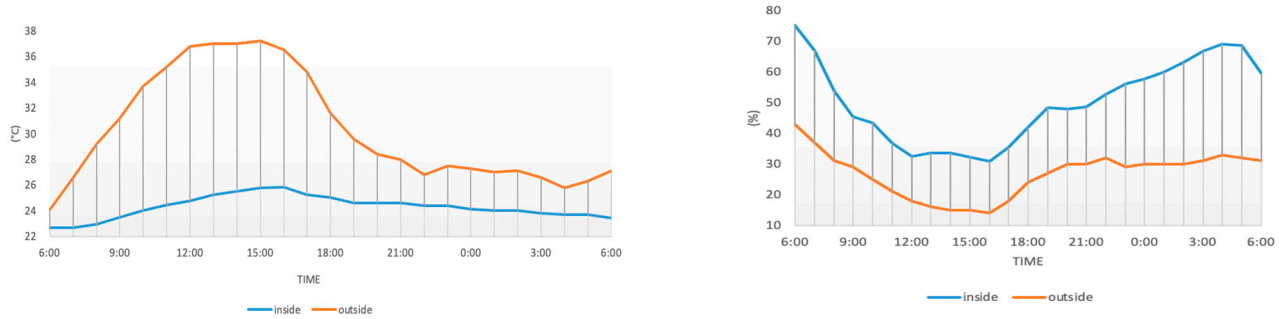
Figure 6. Experimental results for the no-watering scenario: (**a**) inside and outside temperature; (**b**) inside and outside humidity.



(**a**) (**b**)

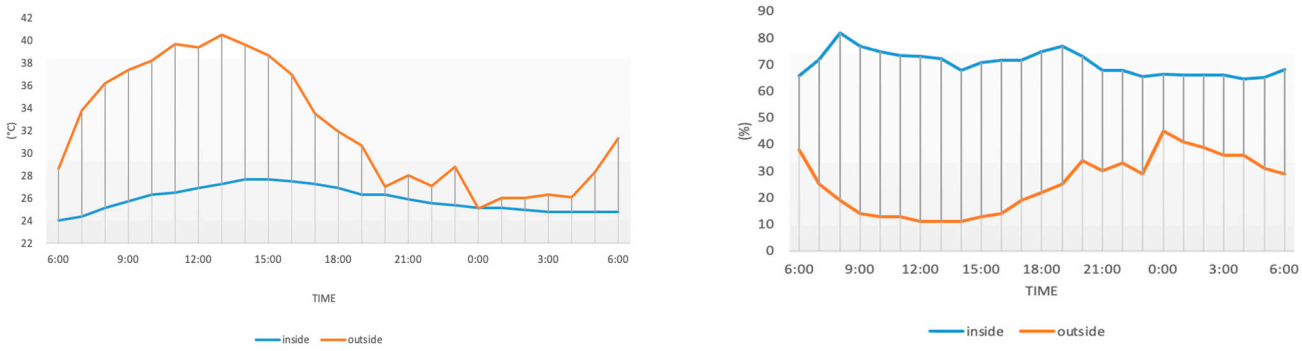
Figure 7. Experimental results for the 40 L/day scenario: (**a**) inside and outside temperature; (**b**) inside and outside humidity.

From these figures, one can observe that the 3C works almost as a temperature and humidity filter in which internal temperature and humidity are steady while external conditions vary significantly. Only Figures 7 and 8 show a high variance in humidity and the reason for which is being investigated. The results presented in Figure 10b show the most evident buffering effect of the 3C, where the external humidity has an accentuated increase due to rain, while the internal stay steady.



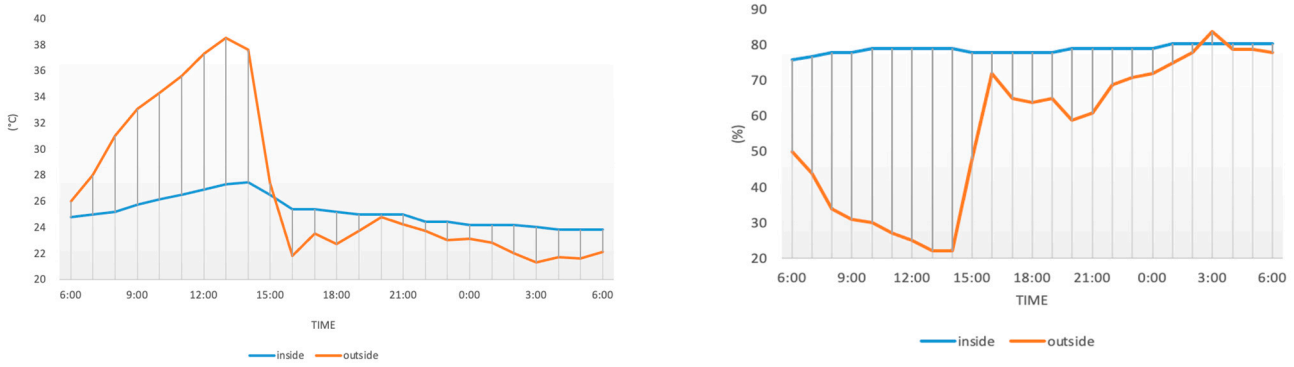
(**a**) (**b**)

Figure 8. Experimental results for the 100 L/day scenario: (**a**) inside and outside temperature; (**b**) inside and outside humidity.



(**a**) (**b**)

Figure 9. Experimental results for the 200 L/day scenario: (**a**) inside and outside temperature; (**b**) inside and outside humidity.

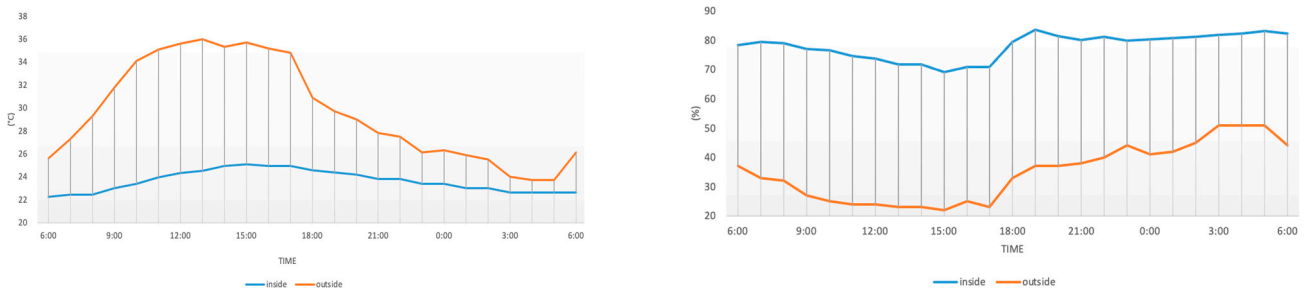


(**a**) (**b**)

Figure 10. Experimental results for the 400 L/day scenario: (**a**) inside and outside temperature; (**b**) inside and outside humidity.

From the figures displaying day-long temperature profiles, it can be observed that the cooling effect of 3C is more evident at high temperatures (higher temperature gain), which occur during daylight (between 8:00 to 18:00). This is a relevant conclusion because 3C was primarily designed for sub-Saharan regions for food preservation during hot and dry seasons.

Figures 7 and 10 indicate periods when the internal temperature is higher than the external. Under closer examination, one can see that they occur during a period of low external temperature and high humidity, which are adverse environmental conditions for evaporative cooling, proving that 3C is properly functional as an evaporative cooler.



(**a**) (**b**)

Figure 11. Experimental results for the 800 L/day scenario: (**a**) inside and outside temperature; (**b**) inside and outside humidity.

Because 3C was built on a 1:1 scale, outdoors, the outside temperature and humidity could not be controlled, and the watering scenarios could not be evaluated for the same environmental conditions. It is possible to observe that for all scenarios, even for the one without watering, the 3C showed significant temperature gain for the high-temperature periods of the day. During the nighttime, when the outside temperature drops and humidity rises, the temperature gain is smaller, but the inside temperature is still low and somewhat suitable for food preservation.

4.2. 3C Saturation Efficiency

The temperature and humidity gains for all watering scenarios were shown in the previous subsection. However, since the environmental temperature and humidity could not be controlled, no conclusions could be reached about the external to internal temperature drop and humidity rise (i.e., regarding the 3C gains).

In other words, a complete evaluation of 3C efficiency would require a facility to produce an environment in which temperature and humidity could be controlled so that identical external conditions could be established for all watering scenarios. However, in the absence of such a facility, the determination of the optimal watering volume was left to be performed using 3C's simulation model.

To improve the assessment of the 3C's ability to perform its mission, the saturation efficiencies were calculated for all scenarios. Figure 12 shows the six psychrometric charts for the 3C operating in those scenarios and the saturation efficiency that was calculated based on such charts plotted for the highest temperature gain.

Using Equation (1), the saturation efficiency was calculated. Table 7 shows the bulb temperature of the air entering the cooler ($T_{e,db}$), the dry bulb temperature at the outlet of the cooler ($T_{l,db}$), the wet bulb temperature at the inlet of the cooler ($T_{e,wb}$), and the saturation efficiency for the six scenarios. Due to the short period of the tests, and the weather variance, the saturation efficiency at the same operation condition for different watering volumes was not possible, and therefore the optimum volume could be determined. However, in comparison with others, it presented a good performance for all scenarios, mainly considering that the 3C is a community scale cooler, while the others are of very small volumes. Table 8 presents an efficiency comparison of 3C and five other evaporative coolers in the literature.

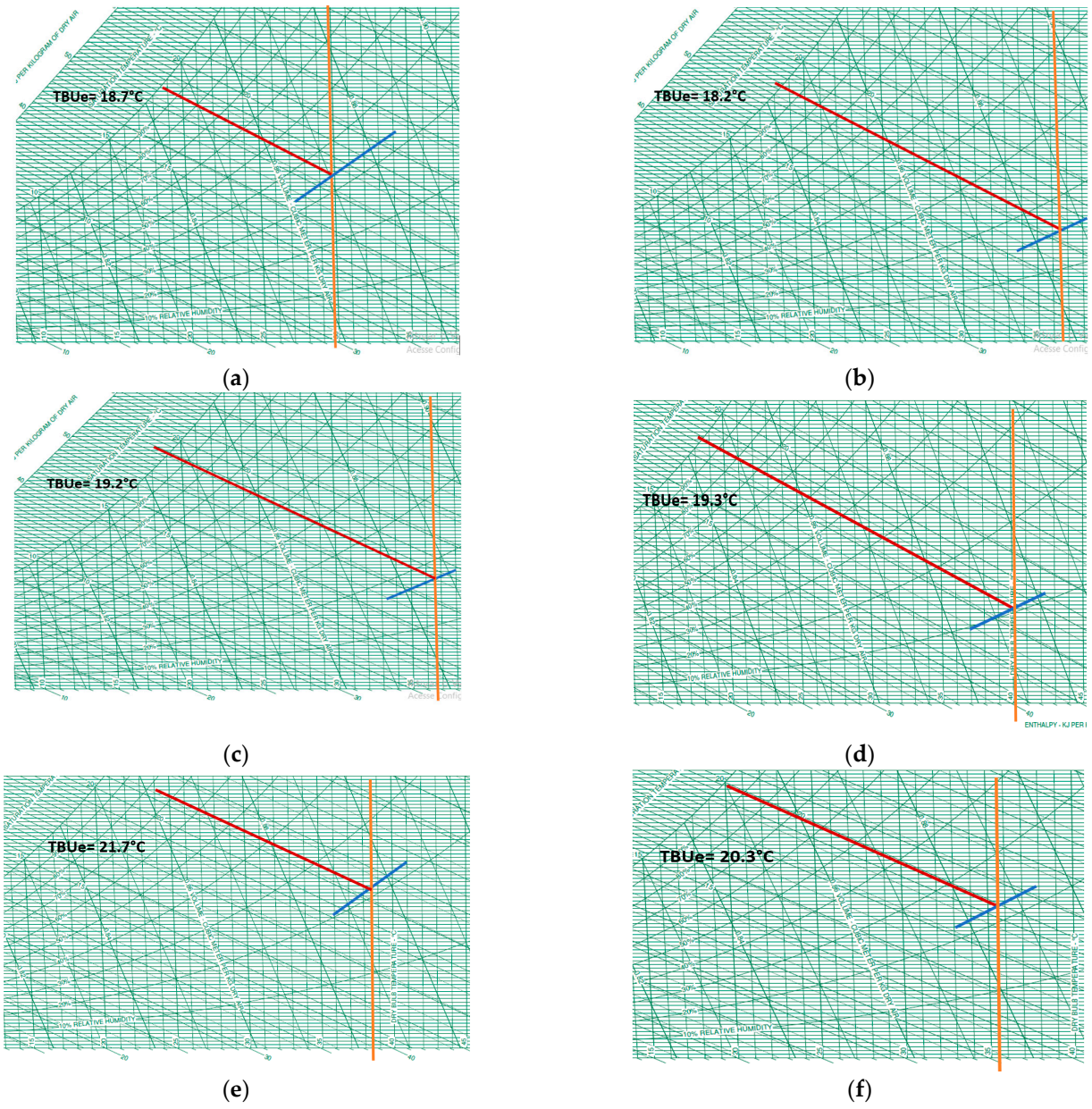


Figure 12. Psychrometric charts: (**a**) no watering; (**b**) 40 L/day watering; (**c**) 100 L/day watering; (**d**) 200 L/day watering; (**e**) 400 L/day watering; (**f**) 800 L/day watering.

Table 7. Saturation efficiency for the six scenarios.

Watering Scenarios (Liters/day)	$T_{e,db}$ (°C)	$T_{l,db}$ (°C)	$T_{e,wb}$ (°C)	ε (%)
0	29.8	21.64	18.7	73.51
40	36.7	24.72	18.2	64.75
100	36.8	24.77	19.2	68.35
200	40.5	27.26	19.3	62.45
400	38.5	27.28	21.7	66.78
800	35.6	24.34	20.3	73.59

Table 8. Efficiency comparison of different evaporative cooler models.

Evaporative Cooler Model	Volume (m^3)	Efficiency (%)
Clay Evaporative Cooler [31]	0.23	20–90
Evaporative cooler for sweet potatoes storage [5]	0.27	87.17
Evaporative Cooling Barn [38]	18.81	127
Zeer pot [26]	0.025	79.31
Active Evaporative Cooling System [17]	0.16	86.01
3C	9.7	62.45–73.59

5. Conclusions

This work presented the Cerrado Cooler Chamber, a community-scale evaporative cooler designed and implemented based on an appropriate technology framework and aligned with the SDGs. It was constructed using cement-stabilized adobes, therefore massively based on earth, a locally available natural resource. Besides being low cost and durable, it is also humidity resistant, with an expected long useful life span. Furthermore, adobe masonry is a vernacular building construction system which is very familiar to rural communities in many countries. It exempts expensive tools, can be made on-site using a few diversities of industrialized materials, and is easy to understand, so 3C can be easily replicated.

The resulting temperatures are insufficient to prevent fruit and vegetables from ripening but can avoid losses and damages from temperatures above 30 °C [39]. The lower temperatures combined with high humidity can increase shelf life [4,6,11–14,17,23]. Furthermore, the designed cooler has the potential to be more effective in dryer and hotter climates.

The Cerrado Cooler has around 8 m^3 (2.10 m × 2.10 m × 2.20 m) and can preserve a load of 1.1 tons of food. Its cost is about 27% of the average cost of other evaporative coolers reported in the literature, i.e., it costs U% 0.27 cents per kilogram, while the average is U$1.00. The efficiency ranges from 62% to 73%, which is a little smaller than the presented in the literature, but still at a considerably high level. Since the 3C could not be tested for different watering volumes, maintaining the same outside temperature and humidity, a fair comparison could not be made to find the optimum volume of water. The 3C is being modeled aiming at watering volume optimization, and results will be presented in future work. Summing up, the 3C is low-cost, easy to implement, fairly efficient, ready to be deployed, and fully capable of fulfilling the mission of an evaporative cooler.

Author Contributions: Conceptualization, A.N.Y. and J.O.P.P.; data curation, K.M.D.; formal analysis, K.M.D.; funding acquisition, A.N.Y.; methodology, K.M.D., A.N.Y. and J.O.P.P.; resources, J.O.P.P.; supervision, A.N.Y. and J.O.P.P.; writing—original draft, K.M.D. and J.O.P.P.; writing—review and editing, A.N.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. The APC was funded by the Federal University of Mato Grosso do Sul.

Data Availability Statement: Data are contained within the paper.

Acknowledgments: The present work was carried out with support from the Federal University of Mato Grosso do Sul—UFMS/MEC—Brazil and it was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001. The authors acknowledge the technical support given by Ronaldo Dias, Thyago Estrabis, Felipe Monteiro, Fabio Trevisan, Marcio Portela, Marcio Kimpara, João Marcos dos Anjos, Seu Antônio, Priscila Nakamura, Raymundo Cordero, Renata Reis, Gabriel Gentil, Arthur Silva.

Conflicts of Interest: The authors declare no conflict of interest.

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