



Review



# Evaporative Cooling for Agricultural Preservation: Technologies, Challenges, and Future Prospects

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**Abstract:** Postharvest food loss remains a major challenge to global food security, particularly in tropical and sub-tropical regions where conventional refrigeration is not feasible, either due to economic or logistical reasons or both. This review critically assesses the development, classification, performance, and prospects of evaporative cooling technologies for agricultural produce preservation. A performance gap in humid climates was identified, and technological and socio-economic barriers limiting widespread adoption are outlined. Unlike previous reviews, a comparative meta-analysis of system effectiveness across diverse environmental conditions and design types is incorporated. Also, the potential of novel desiccants such as metal-organic frameworks (MOFs) is evaluated, and a future research roadmap focused on techno-economic modelling, environmental impact assessments, and integrated design strategies is proposed. The review concludes with practical recommendations for system optimisation and policy interventions to support smallholder adoption.

**Keywords:** post-harvest loss; evaporative cooling; agricultural; preservation

## 1. Introduction

The vapour compression method is the most common approach to preserving agricultural products at low temperatures, but it is costly and relies on environmentally harmful working fluids. As a result, there is growing interest in more affordable and environmentally friendly alternatives, especially for remote areas. One such method is evaporative cooling, which uses water to cool air through evaporation. Although it does not reach the low temperatures of vapour compression refrigeration, it is effective in extending the freshness of fruits, vegetables, and other farm produce, helping to minimise postharvest losses and improve food security. As a result, interest in evaporative cooling for agricultural preservation continues to grow. Evaporative cooling depends on the evaporation of water into unsaturated air, increasing humidity while generating a cooling effect. The process is governed by the psychrometric and thermodynamic properties of air, especially the wet-bulb depression; a larger difference between the dry-bulb and wet-bulb temperatures indicates lower relative humidity and a stronger cooling potential. This method is most effective in arid regions, though ongoing efforts seek to enhance its performance in humid areas.

Evaporative coolers can be classified as direct or indirect. In direct evaporative cooling, cooled air is introduced directly into the space needing cooling. Conversely, indirect evaporative cooling uses a heat exchanger to cool the space with air that has undergone evaporation. While direct evaporative cooling results in high humidity levels in the cooled space, making it unsuitable for comfort cooling, it is highly effective in preserving agricultural



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produce, where humidity is crucial. Hence, direct evaporative coolers are mainly utilised in agriculture for storing farm produce. Indirect evaporative coolers, although unable to achieve temperatures as low as direct ones, are more commonly used in comfort cooling for indoor environments. According to [1], approximately 50% of evaporative coolers for post-harvest storage are direct active, 30% are direct passive, and 20% are indirect. Notably, smallholder farmers in low- and medium-income countries primarily use the direct passive type. Various designs of evaporative coolers exist, ranging from simple straw-packed structures to more sophisticated models [2]. Regardless of the type or complexity of the design, all evaporative coolers share a fundamental characteristic: they are constructed from materials capable of retaining moisture.

The evaporative cooling principle for preserving agricultural produce can be implemented in two ways: passive direct evaporative cooling systems and non-passive (active) direct evaporative cooling systems. The main difference between them lies in how they manage airflow. While passive systems depend on natural wind, non-passive (active) systems use fans to move air. Several studies have evaluated the performance of these cooling methods. Some recent detailed reviews and their scope are shown in Table 1. This review adds by combining empirical data, analysing performance patterns across different regions, and offering a comparative view for system classification. Unlike earlier descriptive reviews, we critically examine performance metrics, emphasise links between design and performance, and explore emerging technological areas like MOF-based desiccant systems.

**Table 1.** Recent review works on evaporative cooling.

Review	Scope and Focus	Limitations
[3]	Deployment mapping, performance evaluation of passive coolers	Focused mainly on geographic suitability; limited treatment of advanced materials or socio-economic adoption
[4]	Regional review of evaporative cooling systems, decision-support tools, desiccant-assisted systems	Strong regional focus but limited lifecycle/environmental analysis; no advanced MOFs
[5]	General overview of evaporative cooling systems for vegetables	Descriptive, focused on affordability and basic performance
[6]	Technical review of evaporative cooling systems and desiccants in greenhouse settings	Narrow scope (greenhouses), not tailored to postharvest storage or socio-economic realities
[7]	General overview of brick wall coolers storage system, focusing on the development and progress made, including economics and environmental impact	Focused only on the brick wall cooler storage system (zero energy storage)
[8]	Comparative and regional review of traditional evaporative cooling methods	Concentrated on traditional evaporative cooling methods and limited to Eastern Africa
[9]	Comparative study of zero energy storage systems in India, with emphasis on socio-economic condition of the small and marginal farmers	Focused only on feasibility studies and zero energy storage systems in India

### 1.1. Novelty

This review stands out by shifting from descriptive surveys to a comparative, integrative, and future-oriented analysis of evaporative cooling systems. Unlike previous reviews that merely catalogued designs or case studies, it conducts a meta-analysis across different regions and system types, explicitly connecting design choices to outcomes like temperature reduction, humidity increase, and extension of shelf life. It progresses the field by introducing Metal-Organic Frameworks (MOFs) as next-generation desiccants, tackling the limitations of traditional materials in humid climates. Additionally, the review places evaporative cooling within a techno-economic and environmental framework, emphasising the need for lifecycle assessments, sustainability evaluations, and integrated modelling—elements often missing in earlier studies. Lastly, it includes socio-economic and policy considerations, highlighting barriers to adoption and proposing interventions such as public-private partnerships, subsidies, and farmer education. Collectively, these insights position evaporative cooling as a scalable, sustainable, and socially embedded strategy for reducing postharvest losses in Sub-Saharan Africa.

### 1.2. Review Methodology

The review was conducted in accordance with the widely accepted review procedures established by [10]. It was divided into three phases: (i) The planning phase, where the research question was defined and the need for the review was identified. Thus, the review direction was set at this stage; (ii) The conducting phase, during which databases were identified. To ensure broad coverage of sources, databases that provide information from diverse, varying-quality sources were combined. The main databases used included Web of Science, Scopus, Google Scholar, EBSCO Information Services, and DOAJ. Predefined keywords were used in the search and relevant research articles were identified, filtered, and carefully examined; (iii) The articles were grouped based on the type of technology used and the nature of the study, then thoroughly reviewed in accordance with the study's objectives.

The two main groupings were the Direct Evaporative Coolers and the Indirect Evaporative Coolers. The direct type was further divided into Direct Active and Direct Passive systems. Additionally, a separate group of Theoretical studies was considered. Throughout the search, emphasis was placed on evaporative cooling for agricultural purposes, as evaporative cooling is also used for comfort cooling in air conditioning.

Data were extracted on study characteristics and outcome variables, including shelf life, temperature depression between storage space and ambient temperatures, relative humidity increase in the storage space, cooling efficiency, and production cost. These data were analysed statistically, using mean values, and synthesised using a random-effects model to account for between-study variability.  $I^2$  statistic was used to assess statistical heterogeneity, and where sufficient data were available, subgroup analyses were conducted by product type, cooling system design, and climatic conditions.

## 2. The Direct Evaporative Coolers

### 2.1. The Direct Passive Evaporative Cooler

These are low-cost systems and require no electricity; hence, they can be built on farms for temporary storage of freshly harvested fruits and vegetables. They can be grouped as pot-in-pot coolers, zero energy cooling chamber (ZECC), and charcoal coolers. Refs. [1,11–29] have studied this type of evaporative cooler. Data from prototype and field testing show an average temperature drop of 3–12 °C, RH gains of 20–80%, and shelf-life extension of 3–30 days. Some of the reported shelf-life improvements were achieved after either pre-treating the farm produce before storing it in the evaporative cooler [13,22,23] or using specially prepared storage containers before placing them in the storage chamber of the evaporative cooler [20]. A summary of the specific performances of some of the reported systems, as presented by the authors, is shown in Table 2. Ref. [28] also studied the effect of water supply frequency on the cooler performance by considering three different watering regimes; once at 8:00 h, two times at 8:00 and 12:00 h, and three times at 8:00, 12:00 and 14:00 h and concluded that triple watering of the cooler produced the best result of 11 °C temperature decrease and 38% RH increase and maintained the recommended RH of 80 to 95% for horticultural produce, although the temperature was higher than the recommended 0–10 °C.

#### 2.1.1. Performance Comparison of Different Direct Passive Evaporative Cooler Types

The ZECC and pot-in-pot coolers are popular among passive systems because they are simple and affordable. Evaluations of their performance across different regions [30,31] and user surveys [31] show that farmers are satisfied with these systems, citing their ease of use and maintenance. Ref. [30] noted that although these coolers may not always produce large average temperature drops, they provide benefits like higher humidity, lower daily temperature peaks, and reduced fluctuations, all of which help extend shelf-life. The pot-in-pot system performed better than the brick ZECC, with an average temperature drop of 8 °C, though its small storage capacity (~5 L) limits its application. In Rwanda, farmers reported a 2–4 day extension in shelf-life, with average RH of about 95% in both systems. In Malawi, Ref. [32] found that the charcoal coolers, ZECC, and pot-in-pot systems achieved temperature reductions of 2–16 °C and RH increases of 24–42%. The pot-in-pot cooler experienced the lowest weight loss at 5.2% during the dry season, while the ZECC had the lowest in the wet season at 5.15%. Tomato shelf-life was extended to 24 days across both seasons. However, the charcoal coolers had the highest construction costs. In Nairobi, Ref. [33] recorded temperature ranges of 15.5–20.5 °C for the charcoal cooler and 18–20 °C for ZECC, both below ambient by 1–10 °C. RH inside the charcoal cooler ranged from 75–100%, while it remained at 100% inside the ZECC. Vegetables stored in both systems stayed viable for 3–5 days.

#### 2.1.2. Performance Improvement/Optimisation Studies of Direct Passive Evaporative Coolers

Efforts to enhance the performance of direct passive cooling systems often focus on construction materials. Ref. [14] found that a sand-clay mix produced the highest RH in the storage chamber. Ref. [34] compared riverbed sand and rice husk ash, reporting that rice husk ash offered higher water retention and RH, while sand achieved lower chamber temperatures. Ref. [35] observed that applying 100 L/day of water improved ZECC performance, extending brinjal shelf-life by 9 days. In contrast, Ref. [36] identified 45 L/day as the optimal amount for tomato storage, extending shelf-life from 7 to 16 days, superior to 30 L or 60 L/day. These findings suggest an optimal water level exists. Excess water can reduce cooling efficiency by saturating the filler and decreasing evaporation due to reduced porosity. Ref. [28] supported this, noting that watering thrice daily yielded the best results, balancing moisture without compromising porosity. Overall, system performance depends not only on ambient humidity and pad material but also on watering strategy and airflow dynamics.

**Table 2.** Performance summary of some reported evaporative cooling systems.

S/No	Type of Evaporative Cooler	Produce Type Stored	Cooler Temp. and RH [Max. Cooling Efficiency]	Ambient Temp. and RH	Product Storage Area	Shelf-Life	Authors
1.	Direct-Passive Charcoal type	Tomatoes and Kales	9.2 °C <sup>a</sup> , 36.8% <sup>b</sup> [91.5%]		Vented plastic crate inside the cooling chamber	Extended (Number of days not specified)	[27]
2.	Combined Indirect air cooling and direct evaporative cooling	Tomatoes (green-breaker stage and pink)	14–20 °C, 87.8–97.4%	20–31.9 °C, 46.6–80.7%	Crates inside the cooling chamber	Extended for tomatoes at green-breaker stage	[37]
3.	Direct- Active type	Red and green tomatoes	23.7 °C, 95.6% [86.01%]	29.5 °C, 64.7%		Extended (Number of days not specified)	[38]
4.	Direct-Active type	Tomatoes and Bananas	1.40–3.40 °C <sup>a</sup> , 9.30–20.30% <sup>b</sup> [85.53%]				[39]
5.	Direct-Active type	Tomatoes	23–27 °C <sup>c</sup> , 81–96% <sup>c</sup> [81% <sup>c</sup> ]	25.9–33.20 °C <sup>c</sup> , 66–73% <sup>c</sup>		Extended by 5 days Extended (Number of days not specified)	[40]
6.	Direct-Active type	Pumpkin and Amaranths leaves	23.2–25.8 °C, 34–73% [77–98%]	29.9–37 °C, 85.6–96.8%		Extended (Number of days not specified)	[41]
7.	Direct-Passive Charcoal type (used charcoal blanket)	Apples	5 °C <sup>a</sup> , 85–95% (laboratory test); 2–3 °C <sup>a</sup> (Field test), >90% [60%]		Ventilated box		[1]
8.	Direct-Active type	Oranges, Green tomatoes and Red tomatoes	22.8 °C, 95.70%	29.5 °C, 64.69%			[42]
10.	Direct- Passive type	Tomatoes and Grapes	19–25 °C, 80–99% [70–95%]	29–35 °C, 12–37%		Extended (Number of days not specified)	[12]
11.	Direct-Active type	Tomatoes and Carrots	16–26 °C, 33–88%	26–32 °C, 18–31%		Extended by 14 days	[43]
12.	Direct-Active type	Tomatoes	13.75–14.75 °C <sup>c</sup> , 78–85.5% <sup>c</sup> [71–87.5%]	21.5–22.25 °C <sup>c</sup> , 45–58.8% <sup>c</sup>		Extended by 3 days	[44]
13.	Direct- Passive (ZECC) type	Tomatoes	17–23 °C (Sunny day), 16–22 °C (Rainy day), 77–83% (Sunny day), 72–79% (Rainy day)	27–42 °C (Sunny day) 22–29 °C (Rainy day)			[31]
14.	Direct-Active type	Tomatoes, Mangos, Bananas, Carrots	20.6 °C <sup>c</sup> , 96.8% <sup>c</sup>	35 °C, 44%		Extended by 9–20 days (depending on product)	[45]
15.	Direct-Passive type	Tomatoes, Hot pepper	20–23.5 °C, 51–93% (for tomatoes) 20.5–26.5 °C, 49–95% (for hot pepper)	25–28 °C, 47–58% (for tomatoes) 28–30.5 °C, 47–57% (for hot pepper)	Trays made from wire mesh and wood		[46]
16.	Direct-Passive (ZECC) type	Citruses (Lime, Lemon, Citron, Pomelo, Mandarin orange)	5–6 °C <sup>a</sup> , 10–15% <sup>b</sup> (during summer) 10–11 °C <sup>a</sup> , 20–23–no load <sup>b</sup> 16–17–loaded <sup>b</sup> (during winter) [55–97%]			Extended by 20–35 days	[17]
17.	Direct-active type combined with indirect air cooling		7–16 °C <sup>a</sup> , 13–41% <sup>b</sup> [88.04–95.6%]				[47]
18.	Desiccant (activated carbon) enhanced direct-active type		10.83–14.28 °C <sup>a,c</sup> , 59.94% <sup>b,c</sup> [94.25%]				[48]
19.	Direct-passive (charcoal) type	Amaranth, Spinach	16–22 °C, 67–87%	22–33 °C, 49–77%		Extended by 5–6 days (depending on product)	[24]
20.	Direct-passive (ZECC) type	Tomatoes	36.5–38.5 °C, 74–76%	37–39.5 °C, 71.5–74%		Extended by 3 days	[16]
21.	Direct-passive (charcoal) type		20–24 °C, 70–98%	24–32 °C, 36–72%			[28]
22.	Direct-passive (double wall-clay) type	Eggplant, Stem amaranth	19.9–20.8 °C, 88–94% (no load test) 19.4–20.3 °C, 73–93% (loaded test)	24–29 °C, 50–71% (no load test) 21.3–27.8 °C, 44–82% (loaded test)		Extended by 3–5 days (depending on product)	[14]

Table 2. Cont.

S/No	Type of Evaporative Cooler	Produce Type Stored	Cooler Temp. and RH [Max. Cooling Efficiency]	Ambient Temp. and RH	Product Storage Area	Shelf-Life	Authors
23.	Direct-passive (ZECC) type	Leafy Amaranth vegetables	18–20.0 °C, 100%	15.3–29 °C, 46–97%		Extended by 3–5 days	[33]
24.	Direct-passive (charcoal) type	Leafy Amaranth vegetables	15.5–20.5 °C, 75–100%	15.3–29 °C, 46–97%		Extended by 3–5 days	[33]
25.	Direct-passive type	Different fruits and vegetable	10–15 °C <sup>a</sup> , 30–40% <sup>b</sup>			Extended by 3–5 days	[16]
26.	Direct-passive (clay-cabinet) type		1.0–8.2 °C (Wet season), 3.0–12.0 °C (Dry season)				[11]
27.	Direct-passive (charcoal) type	Cucumber	19.71–24.82 °C <sup>c</sup> , 93–95% <sup>c</sup> [50–100%]	26.32–28.65 °C <sup>c</sup> , 12–95% <sup>c</sup>		Extended (Number of days not specified)	[25]
28.	Direct-Active type	Avocado	25.0 ± 0.37 °C <sup>c</sup> , 76.8 ± 1.6% <sup>c</sup> [83.0%]	2.1 ± 0.99 °C <sup>b</sup> , 43 ± 2.8% <sup>c</sup>		Extended (Number of days not specified)	[49]
29.	Direct-Active type	Banana, Papaya, Orange, Mandarin, lemon, Mango, Tomato, Carrot	16.4–21.5 °C, 84–91.1% [55–84%]	25–36 °C, 31–50%	Three equally spaced shelves	Extended. (Products in 100% marketable state after 15 days of storage)	[50]
30.	Direct-passive type	Tomato	7.5–25.30°C, 64.67–97.67% [55–94.7%]	6.0–31.0 °C, 57–60%		Extended by 3–13 days depending on the filling material.	[51]
31	Direct-Active type	Tomato, Carrot, Green chilli (pepper)	16.2–22.1°C, 75–90% [82%]	22.6–29.8 °C, 66–80%		Extended by 12 days	[52]

<sup>a</sup> Difference between ambient temperature and cooler temperature; <sup>b</sup> Difference between ambient RH and cooler RH; <sup>c</sup> Average daily values.

### 2.1.3. Theoretical Studies of Direct Passive Evaporative Coolers

Some theory-based studies have been reported on passive evaporative coolers used for preserving fruits and vegetables. Ref. [53] concluded from their model that air velocity over the moist surface significantly influences achieving low temperatures. Besides air velocity, the surface area of the moistened surface also importantly impacts the performance of the direct-type passive evaporative cooler. Ref. [54] found that the evaporative cooler model performs best during the dry season but can maintain the storage chamber temperature below the ambient temperature throughout the year, regardless of the season. Ref. [3] developed easy-to-use tools to better identify regions with the highest potential for direct passive evaporative coolers, ensuring they are installed only in locations that would yield good results. Ref. [55] employed a two-dimensional unsteady mathematical model to examine the performance of a clay pot refrigerator and the effects of ambient conditions on the mass transfer coefficient, evaporation loss, and hydraulic conductivity of clay and sand. The developed model was validated using experimental results obtained in an environmental chamber.

## 2.2. The Direct Active Evaporative Cooler

Direct active evaporative coolers are powered by fans or blowers, which enhance airflow and cooling efficiency. Different designs, ranging from simple models to complex systems, have revealed cooling efficiencies >80% and shelf-life improvements exceeding 14 days for tomatoes and mangoes. However, energy needs limit the application in off-grid areas. Refs. [38–40] reported cooling efficiencies of 85–87% with notable shelf-life improvements. Refs. [41,42] tested single- and triple-fan configurations, achieving 4–13 °C temperature drops, 95–97% RH, and quality preservation. Ref. [43] noted a 14-day shelf-life gain, 16–26 °C cooling, and 33–88% RH rise. Ref. [44] observed a 3-day extension of shelf life in tomatoes. Ref. [49] achieved 83% efficiency, reduced weight loss (7.5% to 3.9%), 76.8% RH, 7 °C cooling, and longer avocado shelf-life. Ref. [45] extended shelf life for tomatoes (9 days), mangoes (4 days), bananas (7 days), and carrots (12 days), with 7.8–15.5 °C cooling and RH from 44% to 96.8%. Ref. [37] found temperature drops of 0.22–5.2 °C (wood shavings) and 0.57–10.94 °C (polyurethane) unloaded, and up to 9.88 °C when loaded, with efficiencies of 3.62–60% and 19.9–96.42%, respectively. While active systems outperform passive ones in cooling, the latter remain attractive due to lower cost and no electricity requirement, making them ideal for remote farms post-harvest.

### 2.2.1. Direct Active Systems Performance Improvement Strategies

Refs. [47,56] tested a hybrid system combining indirect air and direct evaporative cooling, achieving storage temperatures 7–16 °C below ambient, RH increases of 13–41%, and cooling efficiencies of 88.04–95.6%. This system offers an effective, low-cost preservation solution for fruits and vegetables in sub-Saharan Africa. To address evaporative cooling limitations in humid conditions, various desiccant-enhanced configurations have emerged. Conventional desiccants like silica-gel and activated carbon improve performance but saturate quickly. Ref. [57] also reported improved evaporative cooler performance with silica gel integration. Ref. [48] found that activated carbon further reduced temperatures in the cooling chamber by 1.5–4.95 °C, with a cooling capacity of 3653 W, effectiveness of 94.25%, and COP of 52.2. Ref. [58] evaluated ARTSorb™, PROSorb™, various silica gels, and their mixtures, concluding that desiccants improve pad efficiency in livestock barns and greenhouses. Emerging materials such as Metal-Organic Frameworks (MOFs), notably MOF-801 and MOF-303, exhibit superior water adsorption capacities across a wide RH range and are being tested for integration into agricultural coolers. MOF-enhanced coolers show promise in achieving consistent temperature reductions of 10–14 °C over non-desiccant setups in high RH zones [59]. Although lab-scale performance is compelling, field deployment is limited due to synthesis cost and regeneration challenges. Composite desiccant beds, solar-thermal regeneration, and coating optimisation are under investigation to scale these solutions effectively.

### 2.2.2. Indirect Systems Applied in Agriculture

Ref. [60] designed, built and tested an indirect active evaporative cooler for the preservation of fruits and vegetables. The evaporative cooler comprises two extraction fans, a cooling pad, a plate-fin heat exchanger, a water tank and the cooling chamber. Results from preserving tomatoes for 14 days in the cooler, compared with storage in a refrigerator and under ambient conditions, showed the refrigerator was the best at maintaining skin firmness, while the evaporative cooler was the best for preserving tomato acidity and total soluble solids. Studies have reported improvements in the performance of indirect evaporative coolers. Ref. [61] explored performance enhancement of regenerative evaporative coolers through surface profile modifications and the use of ternary hybrid nanofluids. While nanofluid application alone yielded only marginal gains due to viscosity-related

penalties, altering the cooling plate geometry, particularly with capsule embossed surfaces, produced significant improvements in COP, exergy efficiency, and sustainability index. Also, finned and corrugated profiles enhanced performance, though less effectively. Thus, geometric surface engineering outweighs nanofluid modification in boosting cooler efficiency, although with an increased pressure drop, higher operating expenses, and greater CO<sub>2</sub> emissions. Ref. [62] presented a systematic numerical comparison of eight regenerative evaporative cooling topologies and evaluated their cooling capacity, dew-point effectiveness, and COP. While noting the high sensitivity of the performance to water inlet temperature, flow rate, and extraction ratio, they observed that two designs (parallel and cross-flow in the wet channel) consistently outperformed other configurations under most operating conditions, thus highlighting regenerative evaporative cooling's potential as an energy-efficient alternative to vapour compression cooling. Although the modifications proposed by [61,62] were used in space cooling for comfort, they can also be extended to indirect evaporative cooling for agricultural produce preservation.

### 3. Comparative Performance of Evaporative Cooling Technologies Used in Agriculture

Table 3 presents a comparative evaluation of evaporative cooling technologies used in agriculture. The assessment relies on field-tested parameters, including average temperature reduction, humidity increase, cooling efficiency, and contextual feasibility metrics such as cost and maintenance requirements. It emphasises the strengths and compromises of different systems across various climatic zones and operational scales. Passive systems like Pot-in-Pot and ZECC stand out for their simplicity and affordability, making them especially suitable for remote or low-income farming communities. However, their effectiveness diminishes in high-humidity conditions. Active and hybrid systems provide improved cooling performance but involve greater complexity, higher initial costs, and more demanding maintenance; factors that may restrict adoption in rural areas. MOF-enhanced systems demonstrate strong potential for humid environments but need further cost reductions and broader field validation for practical scalability. Their current lack of cost competitiveness, caused by material and manufacturing costs, limits widespread deployment. Their viability is expected to improve with economies of scale and innovations in material science.

**Table 3.** The comparative performance of evaporative cooling technologies used in agriculture.

Cooler Type	Climate Suitability	Avg. Temp Drop (°C)	Avg. RH Increase (%)	Cooling Efficiency (%)	Shelf-Life Gain (Days)	Energy Requirement	Material Cost (\$)	User Maintenance
Pot-in-Pot	Arid	5	40	60	5	None	<10	Very Low
ZECC	Semi-arid	8	50	70	10	None	<20	Low
Charcoal Cooler	Tropical	6	45	65	7	None	<15	Moderate
Direct Active	Arid & Humid	12	70	85	14	Moderate	100–200	Moderate
Hybrid (Indirect + Direct)	Humid	14	80	90	16	High	200–400	High
MOF-Enhanced	Humid	13	85	92	15	High	300–500	High

Table 4 summarises key decision-making criteria for selecting an evaporative cooling system. Passive systems are characterised by low investment requirements, zero energy consumption, and minimal operating costs, resulting in short or even negligible payback periods. They are typically built with locally available materials and require limited technical expertise, making them ideal for smallholder use. Active systems deliver superior cooling but depend on external power sources, involve higher capital investment, and demand regular maintenance. These systems are better suited for cooperatives, solar-powered farms, or operations dealing with high-value perishables.

**Table 4.** Summary of the cost-effectiveness of evaporative cooling systems.

Criterion	Passive Systems	Active Systems
Best For	Low-income rural farmers	Small agri-businesses
Initial Investment	Very Low	Moderate to High
Electricity Dependency	None	High (unless solar-assisted)
Suitability in Humid Climates	Low	Moderate
Long-term Affordability	High	Medium

Expanding the global adoption of evaporative cooling technologies will depend on locally adapted designs tailored to agro-ecological zones, international collaboration to accelerate innovation transfer (e.g., composite desiccants, solar-thermal regeneration, modular cooling chambers), and supportive policy frameworks. Alignment with global initiatives such as the Food and Agricultural Organisation (FAO) and the UN Sustainable Development Goals (SDGs) will also be essential to drive investment in low-energy postharvest solutions.

#### 4. Design Considerations

Designing an evaporative cooler for agricultural produce preservation requires understanding the target environment and species. The cooling potential of an evaporative cooler is theoretically the difference between the dry-bulb temperature and the wet-bulb temperature:

$$\Delta T_{max} = T_{db} - T_{wb} \quad (1)$$

$T_{db}$  and  $T_{wb}$  are the air dry and wet-bulb temperatures, respectively. The cooling effectiveness or efficiency is established using the equation for saturation efficiency given as

$$\varepsilon = \frac{T_{db,i} - T_{db,o}}{T_{db,i} - T_{wb,i}} \quad (2)$$

$T_{db,i}$  is the inlet dry-bulb temperature,  $T_{db,o}$  is the outlet dry-bulb temperature and  $T_{wb,i}$  is the inlet wet-bulb temperature. For effective cooling, especially during hotter, drier periods, maximising the cooling effectiveness through appropriate media selection and airflow is crucial. Also, water consumption is a significant factor. The mass flow rate of evaporated water,  $\dot{m}_w$  needed to achieve a certain cooling load,  $Q_{evap}$  can be estimated using the latent heat of vaporisation of water,  $h_{fg}$

$$\dot{m}_w = \frac{Q_{evap}}{h_{fg}} \quad (3)$$

The cooling load  $Q_{evap}$  depends on the airflow rate,  $\dot{V}$ , air density,  $\rho$ , desired temperature drop,  $\Delta T_{actual}$ , and the specific heat of air,  $c_p$ . The cooling load is determined using Equation (4).

$$Q_{evap} = \dot{V} \rho c_p \Delta T_{actual} \quad (4)$$

A good design ensures full pad saturation without excessive water loss. Minimising water usage necessitates efficient water distribution and potentially recirculation systems. Uneven water distribution should be avoided since it leads to dry spots and local hotspots in the pad, with a resultant reduction in cooling performance. For even water distribution and uniform wetting, gravity-fed or drip systems are often used. Also, larger wetted area leads to more water being available for evaporation, resulting to greater cooling effect. Water supply rate,  $W$  is computed using the frontal area of the cooling pad,  $A_p$  and the recommended water application rate,  $R$  through Equation (5).

$$W = A_p R \quad (5)$$

$R$  depends on pad material and porosity, pad thickness, air velocity through the pad and climatic conditions [63], with a higher evaporation rate requiring higher  $R$ . Pad porosity is a measure of the fraction of open space in the cooling pad material that allows air and water to pass through. While higher porosity makes for easier airflow, lower pressure drop, and moderate cooling, lower porosity allows more contact between air and water, and in the process enhances evaporative cooling, but may also restrict airflow and reduce system efficiency. An optimal design values, dependent on the evaporative cooler type, are therefore often used. For the zero-energy coolers, 0.8–0.9 is commonly used.

Air velocity,  $v$ , through the evaporative media is also important for effective evaporation. Higher air velocity increases convective heat and mass transfer, enhancing cooling efficiency. However, too high a velocity can dry out produce or reduce contact time for evaporation. Therefore, using an optimal velocity balances cooling efficiency with gentle airflow to avoid produce damage. It is obtained from  $\dot{V}$  and  $A_p$  as

$$v = \frac{\dot{V}}{A_p} \quad (6)$$

Optimising air velocity ensures good contact time between air and water without excessive pressure drop that would impact fan selection and energy consumption. Ultimately, the design must balance cooling performance, water usage, and energy efficiency. Fan selection is guided by  $\dot{V}$  and  $\Delta P$  and the fan power,  $P_{fan}$  is proportional to both.

$$P_{fan} = \frac{\dot{V} \Delta P}{\eta_{fan}} \quad (7)$$

$\Delta P$  is calculated from Equation (8)

$$\Delta P = \left(\frac{\mu L}{K}\right)v + (\rho\beta L)v^2 \quad (8)$$

$\mu$ ,  $L$ ,  $K$ ,  $\beta$  are dynamic viscosity, pad thickness, permeability related to porosity and inertial resistance coefficient, respectively.

Air velocity cannot be controlled or optimised in passive systems since they are ambient air driven. Also, ambient air does not get into the cooling chamber because evaporation occurs on the outside walls and through heat transfer the storage chamber is cooled. Thus, for passive systems emphasis should be placed on the heat transfer characteristics of the porous media, aside from the water seepage rate through it and the mass transfer relationship with the ambient air.

## 5. Technical Challenges and Solutions

### 5.1. Poor Performance in Humid Climates

Currently, no commercially available passive system reliably achieves sub-ambient cooling (>5 °C reduction) in environments with high RH (>80%) without reliance on external energy sources. This limitation is particularly critical for tropical and humid climates, where cooling demand is high, and energy access is often constrained. Traditional desiccants (silica-gel and activated carbon) have been used to enhance the cooling system's performance [48]. However, they degrade in performance at high humidity, due to a quick saturation rate [58] and require regular energy input for regeneration or air circulation. To overcome this limitation, the development and evaluation of modular surface systems coated with MOF that can act as passive sorption-based cooling elements is proposed. MOFs offer exceptional surface area and tunable hydrophilic properties [64,65], making them suitable candidates for desiccant-driven cooling applications in high RH environments [59,66]. This will entail the design and fabrication of MOF-coated modules, pilot-scale experimental trials, optimisation of coating parameters, and modelling and simulation to optimise the overall system and generate RH-Temperature-Performance maps for major global climatic zones, to assess feasibility for deployment in tropical, coastal, and equatorial regions.

MOFs show exceptional adsorption properties for water vapour, making them highly promising for integration into evaporative cooling systems, especially in humid climates. Their regeneration can be achieved through low-grade heat of 50–80 °C, depending on the MOF [67]. MOF-801 and MOF-303 are known to regenerate at ~65–75 °C while MIL-101(Cr) can regenerate at ~80–90 °C [65]. Their adsorption capacities are in the range from 0.2–1.2 g of water per g of MOF; MOF-801: ~0.25–0.35 g/g at 25 °C and 30–40% RH, while MOF-303 is ~0.45–0.55 g/g under similar conditions. MIL-101(Cr) is up to 1.0–1.2 g/g at higher humidity levels [68]. These characteristics enhance their air dehumidifying capacity, thus improving the efficiency of evaporative coolers in humid climates. Their fast kinetics and low regeneration temperature make them ideal for coupling with solar-driven cooling. MOFs can sustain a high number of adsorption–desorption cycles (>2000 cycles [64]), without significant loss of capacity, compared to silica gel and other common adsorbents, which often degrade after a few hundred cycles due to pore collapse. Its major shortfall is the current synthesis costs, which are considered high; ~\$100–200/kg for lab-scale MOFs. However, economic feasibility is expected to improve with scalable, green synthesis methods and cheaper precursors. Analyses suggest MOF-based cooling becomes cost-competitive if production costs fall below \$50/kg, especially in regions with high electricity prices and unreliable grids.

### 5.2. Lack of Lifecycle and Environmental Analysis

The environmental and economic impacts associated with passive or advanced cooling system materials remain insufficiently characterised. While these systems are often promoted for their low operational energy use, critical factors such as materials sourcing, embedded water-energy costs, construction resource intensity, and system longevity are rarely evaluated in a rigorous, comparative framework. In contrast, traditional vapour compression systems, though energy-intensive, have well-documented life cycle profiles that facilitate transparent environmental trade-offs. Without robust data on the cradle-to-grave impacts of emerging cooling technologies, particularly regarding material sustainability and water dependencies, it is difficult to determine their true long-term value or justify scale-up over conventional alternatives.

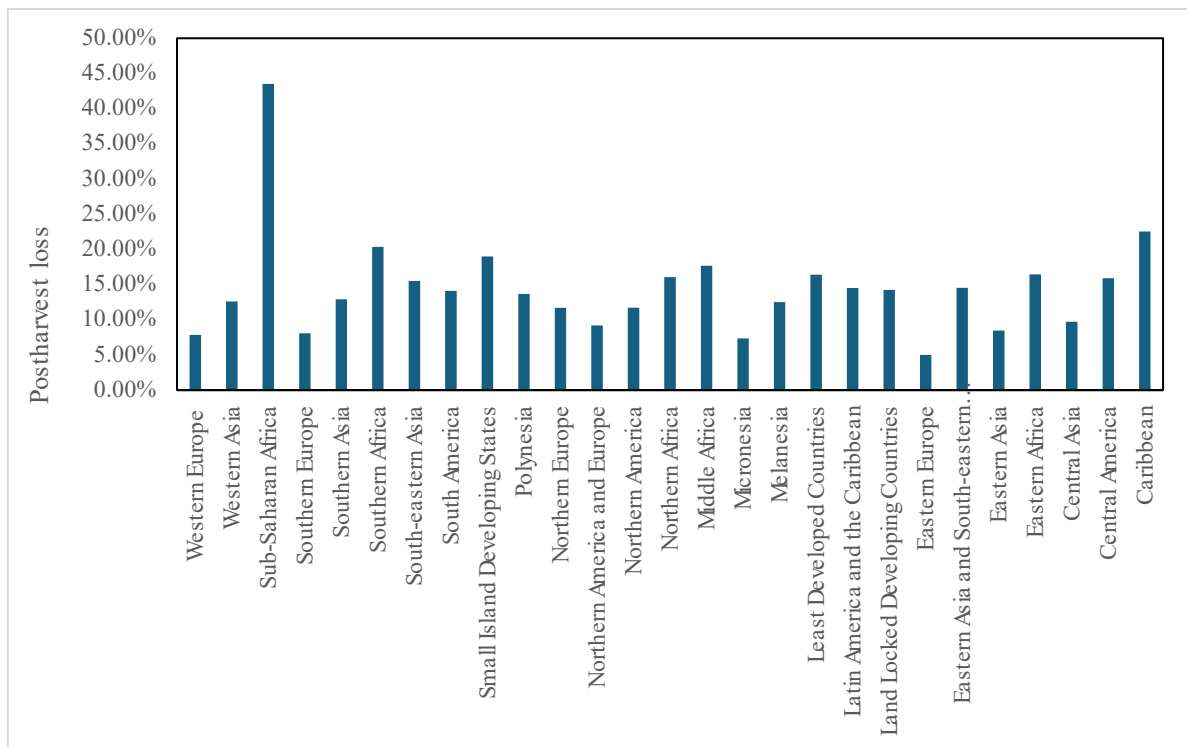
### 5.3. Weak Socioeconomic Integration

Despite growing interest in evaporative cooling systems, there is limited understanding of end-user perceptions, cost-related barriers, and enabling policy frameworks, especially in rural, agricultural, and informal market settings. This knowledge gap hinders effective adoption, customisation, and equitable deployment of cooling innovations for vulnerable populations such as smallholder farmers, informal traders, and peri-urban

dwellers. The key adoption inhibitors include: uncertainty about user preferences, trust, and cultural fit, possible high upfront costs with limited access to capital, lack of awareness or absence of policy incentives for off-grid or passive cooling solutions. To overcome these barriers, public-private partnerships should subsidise initial unit costs and provide tax breaks for manufacturers. Community-led workshops can empower local artisans to build and maintain coolers using locally available materials, and governments should formally include evaporative coolers in postharvest support policies and rural infrastructure plans.

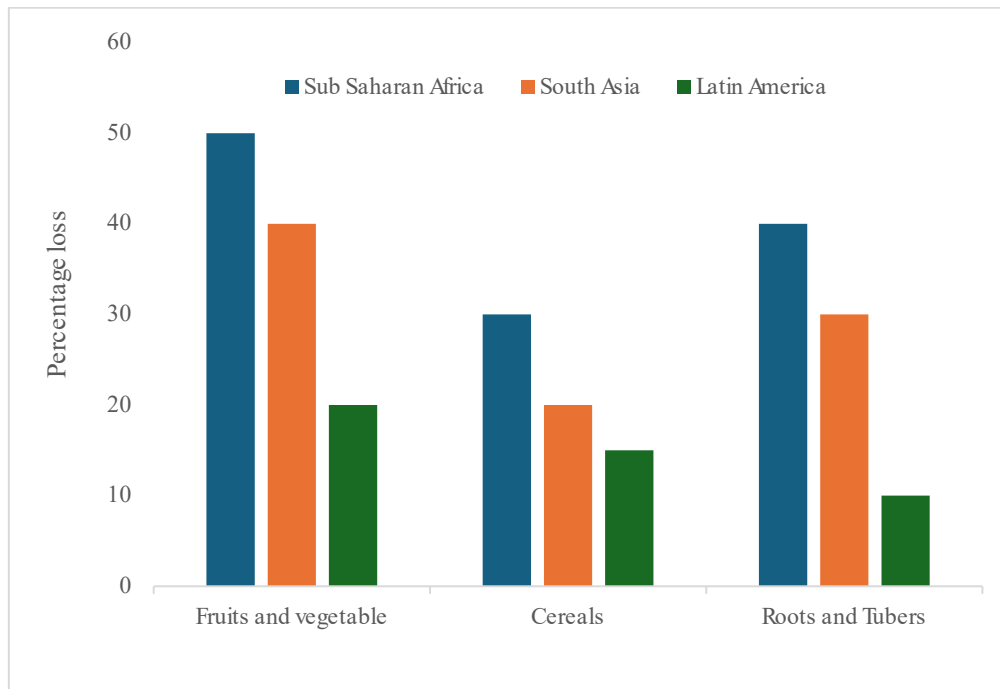
## 6. Potentials

Evaporative coolers in agriculture, for the preservation of fruits and vegetables, have great potential, especially with the increasing impact of climate change on global weather patterns and the global concerns and need for food security. Reduction in the post-harvest losses resulting from heat-induced deterioration soon after harvest is one area where evaporative coolers will significantly impact. It will also play a reasonable role in reducing losses during transportation from the farm to the market and for storage in the markets. According to [69], approximately 14% of the world's food is lost post-harvest before reaching retail, representing \$400 billion annually. Also, post-harvest losses contribute 8–10% of global greenhouse gas emissions, since resources used in production are wasted. Figures 1 and 2 show the regional distribution of the post-harvest losses and the estimated post-harvest loss for different crops in Sub-Saharan Africa, South Asia, and Latin America, respectively. The highest percentage loss is in fruits and vegetables, as shown in Figure 3, followed by roots and tubers, cereals and other crops.

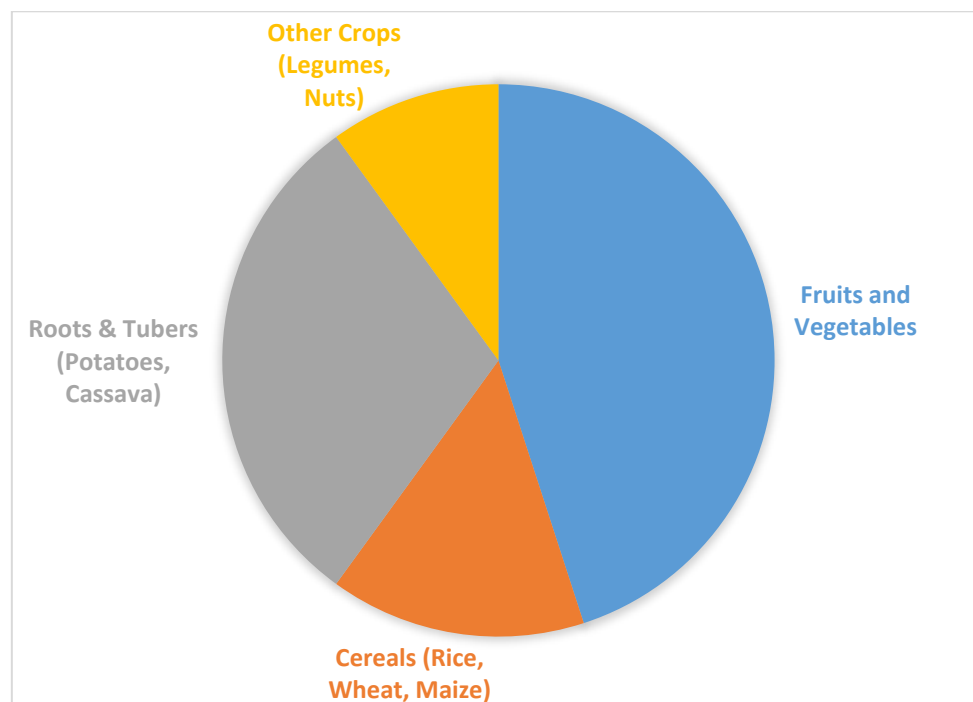


**Figure 1.** Post-harvest loss of agricultural produce per region in 2021 (Data source: [70]).

Fruits, vegetables, roots, and tubers are easily affected by heat, which mostly explains the high percentages recorded in Figures 2 and 3. Interestingly, most fruits, vegetables, roots, and tubers require high humidity and not very low temperatures for preservation; a temperature range of 8–15 °C and RH range of 75–90% have been reported to extend the shelf life of these produce by up to two weeks or more, compared to storage under ambient conditions [71]. This temperature and RH range has been achieved using evaporative coolers, especially during dry periods or in arid or semi-arid areas. Effective deployment of evaporative coolers for preservation can potentially prevent these high losses, since they allow storage at ideal conditions right after harvest for shelf-life extension. This highlights the need to address the poor performance of evaporative coolers during humid periods or in humid locations. Beyond fruits, vegetables, roots, and tubers—where the temperatures and RH levels achieved by evaporative coolers during operation directly match storage requirements—such conditions can also significantly reduce losses in cereals and other crops.



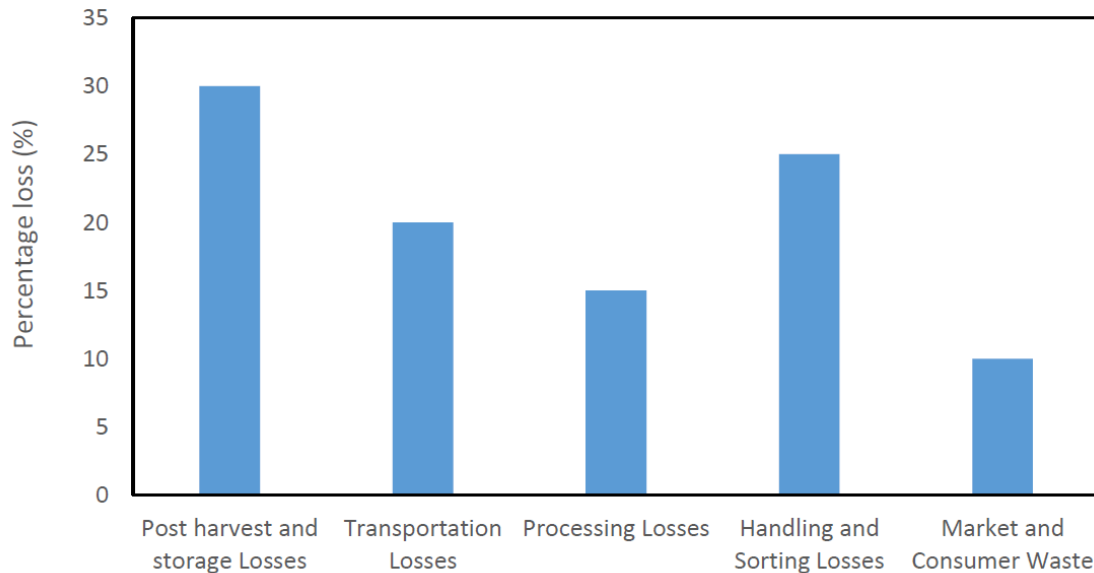
**Figure 2.** Estimated post-harvest loss for different crops in Sub-Saharan Africa, South Asia, and Latin America (Data Source: [72]).



**Figure 3.** Distribution of post-harvest losses across different agricultural commodities globally (Data source: [72]).

Considering the various stages of the supply chain, post-harvest storage losses represent the highest, as shown in Figure 4. Post-harvest loss is highest in sub-Saharan Africa, with as much as 43%. In Nigeria, especially for fruits and vegetables, it is as high as 50% of the annual production, due to a lack of cooling and storage facilities [73]. Evaporative coolers find their best applications in post-harvest thermal management of agricultural produce. They, also, can be deployed in agricultural produce transportation. Evaporative coolers are good alternatives to solve the observed high losses (as seen from Figures 1–4) resulting from either the high cost (installation and running) of conventional cooling systems or the lack of or unreliable electricity supply to power them. Along the food supply chain, its greatest potential is in reducing the 30% lost globally (Figure 4). It will also be useful in reducing transportation losses and storage-related losses in the markets. Their highest potential, however, is in Sub-Saharan Africa, where post-harvest losses are as high as 40%, and this will be mostly in prolonging the shelf life and

preserving the quality of fruits and vegetables (Figure 3). In arid and semi-arid regions, evaporative coolers can be effectively utilised in their current technological state. In regions with high RH, where conventional cooling systems are currently favoured, they can serve as substitutes once the major relative humidity-linked challenge is solved because evaporative coolers are cheap, energy efficient, easy to maintain and operate, environmentally friendly, and can easily be installed in remote farm settlements. The passive ones do not require electrical energy once installed. However, to become fully acceptable, there is a need for proper farmers' education, especially the smallholder farmers, on the benefits of using evaporative coolers.



**Figure 4.** Global post-harvest loss along the food supply chain (Data source: [72]).

## 7. Conclusions

Evaporative cooling systems offer a promising, low-cost, and energy-efficient alternative for preserving agricultural produce, especially in regions where conventional refrigeration is unaffordable or unreliable. This review highlights their effectiveness in reducing postharvest losses, thereby extending shelf life and increasing income generation from farming by smallholder farmers, especially in Sub-Saharan Africa and other low-income countries, and supporting food security. Despite these advantages, the widespread adoption of evaporative cooling remains constrained by technical limitations, mainly due to poor performance in humid climates. Other limitations are environmental, economic, and socio-cultural barriers. Overcoming these challenges requires continued research into innovative materials such as high-capacity desiccants (e.g., MOFs), improved system design through integrated modelling, and participatory approaches that address user needs and local contexts. With strategic investment, interdisciplinary collaboration, and supportive policy frameworks, evaporative cooling can become a critical component of sustainable agricultural storage systems, enhancing resilience to climate change, improving food availability, and reducing global food waste.

## Author Contributions

V.A.J., J.C.N. and. D.O.N.: investigation, visualization; E.S.M.: Formal analysis, Resources; G.N.N.: writing—original draft, methodology; N.V.O.: conceptualization, writing—review & editing, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

### Informed Consent Statement

Not applicable.

### Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

### Conflicts of Interest

The authors declare no conflict of interest.

### Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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