Multidisciplinary Journal of Academic Publications
ISSN (Online): 3107-538X
Vol. 02, Issue 02, March – April 2026

DESIGN OPTIMIZATION AND PERFORMANCE ANALYSIS OF SOLAR-POWERED EVAPORATIVE COOLING SYSTEMS FOR LOW-COST AGRICULTURAL COLD STORAGE: A REVIEW

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Abstract

The annual agricultural loss of agricultural products in developing countries is between 30-40% which is mainly caused by lack of cold storage facilities. The current review paper is a meta-analysis of solar-powered evaporative cooling systems that are applied to the preservation of agricultural products. The article focuses on the development of low-cost cold storage technologies, in particular the solar evaporative cooling systems (SECS) which integrate renewable energy and passive cooling. This study critically analyzes 30 peer-reviewed publications published 2010-2024 to determine different design configurations, cooling performance parameters, cost-effectiveness, and practical implementations. The review of literature points to such key performance indices as coefficient of performance (COP) of 0.65-4.5, 10-25C lower temperature than ambient and preserving relative humidity levels of 85-95%. The critical analysis shows that systems involving photovoltaic panels, which have direct/indirect evaporative cooling, show better performance than isolated systems. This paper will discuss the storage of thermal energy, the psychometric phenomenon, and the criteria of material choice to achieve the optimal performance. Results have shown that these systems have the capacity of extending the shelf life of fruits and vegetables by 200-400 percent with less energy consumption of 60-80 percent than the conventional refrigeration. The paper has addressed implementation issues such as water quality standards, climate-based flexibility and maintenance standards. The future research directions include the integration of the Internet-of-Things, the development of new desiccant materials and multi-stage cooling system designs to achieve higher efficiency in the agricultural setting of the tropical and subtropical areas.

Keywords: *Solar evaporative cooling[1], post-harvest preservation[2], agricultural cold storage[3], renewable energy[4], passive cooling[5].*

1. Introduction

The total agricultural production of the world has been on a record high but post harvest losses of agricultural products have still been a major problem particularly in developing nations where the percentage of lost agricultural products rotting before reaching the consumers is estimated at about 40 percent [1]. The Food and Agriculture Organization (FAO) estimates the post-harvest losses in the world to be approximately 1.3 billion tonnes of food each year in economic and environmental terms of over 680 billion and environmental impact respectively [2]. The most prominent reason behind these losses is poor cold storage facilities at the farm level where the temperatures and humidity conditions are accelerating the process of spoilage, degradation and loss of quality in fresh produce. Although traditional refrigeration is a good idea, it has a number of drawbacks that hinder its application in rural farming societies. They involve the high cost of capital investment (between 150-300 per cubic meter), high operational energy usage (3-8 kWh per cubic meter per day), reliance on the availability of grid power that is not always available in the rural settings and special maintenance needs that are beyond the technical capabilities of the local farmers [3]. Moreover, the traditional vapor-compression refrigerations also use synthetic refrigerants that have high global warming potential, which leads to the problem of environmental degradation and climatic change. Solar evaporative cooling systems (SECS) have been proposed as viable alternatives to these multifaceted challenges and they utilize the plentiful solar energy and natural evaporation. They take advantage of the thermodynamic principle of evaporative cooling, where the evaporation of water takes up latent heat in the surrounding air, thus lowering the temperature and raising the relative humidity, which is most conducive to the preservation of fruits, vegetables, and other perishable agricultural commodities [4]. The technology proves to be especially applicable to small-scale farmers in tropical and subtropical areas with high solar insolation (4-7 kWh/m 2 /day) and low relative humidity during the most important harvest times.

Significance of Solar Evaporative Cooling

Solar evaporative cooling is a paradigm shift in energy consuming refrigeration to the passive, sustainable cooling technologies. The core benefit is the use of water as a cooling medium- a material that is environmental friendly, has zero ozone depletion potential and zero global warming potential [5]. SECS uses renewable solar energy, in either direct passive modes or photovoltaic-driven active elements, unlike conventional systems which have a constant power requirement of electricity, which lowers the operational costs of the system by 75-90 percent of the conventional alternatives [6]. The technology targets key sustainability aspects including economic feasibility; low-capital costs (between 20- 50 per cubic meter), environmental sustainability; zero carbon emissions in operation, social fairness; because farmers with limited resources can access the technology, and food security; with reduced post-harvest losses and longer market access periods [7]. Studies have shown that, when the evaporative cooling is done well, leafy vegetables can last 5-7 days, tomatoes can last 15-21 days and some fruits can last 25-35 days under conditions that are favorable.

Scope and Objectives

This is a review paper that is systematic and analyzes the development, design approach, performance attributes, and implementation plans of solar-driven evaporative cooling systems to agricultural cold storage. The particular objectives are: (1) analysis of underlying principles and thermodynamic processes of evaporative cooling systems, (2) analysis of different design configurations such as direct, indirect and hybrid systems and their relative advantages, (3) analysis of performance parameters under different climatic conditions and agricultural products, (4) analysis of the economic viability and pay-back of various system scales, (5) critical challenges, limitations and failure modes in practical applications and (6) The review includes experimental and computational studies, and field applications in various geographical settings (2010-2024), with evidence-based implications to researchers, engineers, policy-makers, and agricultural stakeholders seeking sustainable post-harvest management options.

2. Survey of Literature

The design of evaporative cooling systems based on solar power has been greatly improved in the last ten years, researchers experimented with different configurations, materials and integration approaches. This part includes a chronological and a thematic overview of major contributions to the field. Initial fundamental studies by Chinenye [9] have defined base standards of performance of the passive evaporative coolers in the tropical climate and revealed that the coolers could reduce the temperature by 10-15 C below the ambient temperature and increase the relative humidity to 85-90%. Their design of clay pot cooler (zeer pot) that did not need any external energy source realized an extension of shelf life of tomatoes and 250% of the leafy vegetables with capital cost less than 15 dollars per unit. The weaknesses however were that it could not perform consistently at high humidity levels and needed to be watered frequently after every 8-12 hours. Dadhich et al. [10] enhanced the technology by conducting methodical research on materials used in evaporative cooling pads, and comparing cellulose, coconut coir, jute and synthetic media. Their experimental findings showed that cellulose pads have the highest cooling efficiencies of 78-82 percent at pressure drops of 25-30 Pa at air velocities of 1.5 m/s whereas natural fiber alternatives had lower efficiencies (60-68 percent) but were much less expensive and biodegradable. The experiment developed important correlations among pad thickness (50-150mm), contact time (0.8-2.5 seconds) and saturation effectiveness.

Combining photovoltaic energy and evaporative cooling was directly studied by Olosunde et al. [11] who designed a 2.5 cubic meter solar powered storage system to use in the storage of tropical fruits. To demonstrate this their system had a 150W PV panel, a 100Ah battery bank and DC fans with a low power draw of 25W which produced internal temperatures of 18-22degC with external ambient temperatures of 35-40degC and the lifecycle cost savings of their system was over 65 percent. The study emphasized the need to have the photovoltaic components sized appropriately to suit the diurnal cooling loads profiles. Ndukwu et al. [12] have done comparative performance assessment of direct and indirect evaporative cooling systems in preserving fruits and vegetables. Direct systems, which have the product air moving over wetted media, were found to have better temperature reductions (15-20 o C) but higher humidity levels (90-95 o C) which were found to be too high in some products such as onions and garlic that are prone to fungal growth. Indirect systems that employed heat exchangers, on the other hand, had moderate humidity (70-80) and temperature reductions of 8-12 C and proved to be suitable to a wider range of products at the expense of higher complexity and capital costs. Chauhan and Agrawal [13] studied innovative hybrid designs of evaporative cooling with thermal energy storage. Their system included phase change materials (PCM) having melting points of 18-22o C to cool down during the night when the evaporative effectiveness of the system reduces. Experimental validation showed that temperatures were stable to within 24 hours without exceeding -3C, which was an improvement of the traditional evaporative systems which fluctuated within +/- 8 C. Nevertheless, integration of PCM raised the first cost by 40-50 and it needed to be optimized economically to suit a certain application.

The study by Lakshmi et al. [14] investigated the multi-stage evaporative cooling designs, which showed the potential of two-stage evaporative cooling (a combination of an indirect and direct cooling stage) to have a wet bulb efficiency over 110% and a temperature drop of 18-25 o C in hot-dry environments. Internal temperatures of their prototype were 15-18 °C at ambient temperature conditions of 40-45 C and relative humidity of 15-25, which could only be maintained by mechanical refrigeration before. The experiment found the best inter-stage combinations and air velocity ratios (1:1.2-1.5) to achieve the highest performance. Kabeel and Bassuoni [15] used computational fluid dynamics (CFD) modeling methods to optimize the distribution of airflow and uniformity of cooling in evaporative cold storage chambers. It was found that the uniformity of the temperature (within a range of ±2 o C) of the product was better with the placement of various small fans than with the placement of a large fan (within a range of ±6 o C), which directly affected the quality of the products. The study came up with design principles of the air circulation of 40-60 air changes per hour as the best option. Jain and Tiwari [16] considered desiccant-enhanced evaporative cooling systems and incorporated silica gel as well as molecular sieves to preprepare ambient air prior to evaporation steps. This design allowed the efficient functioning in the monsoon season when traditional designs cannot work in such situations because of the high humidity in the air. The desiccants could also be regenerated by solar energy during the day time and thus the system could operate continuously although the system was highly complex and needed complex control systems.

Nkolisa et al. [17] conducted economic viability studies to determine the feasibility of implementation of the smallholder farmers in Sub-Saharan Africa. Their evaluation of 45 installations in 3 years showed that farmers obtained the payback period within 18-30 months due to the reduction in spoilage (35-40% reduction) and access to the market (premium prices (20-30% better quality produce). Community-based maintenance training, use of locally-sourced materials to carry out repairs and cooperative ownership models, which spread capital requirements initial requirements, were critical success factors. Adedeji et al. [18] investigated performance optimization using intelligent control systems, and made use of microcontroller-based monitoring and control of the fan speeds, water circulation pumps, and ventilation dampers. Their adaptive control algorithm tuned operating parameters according to real-time measurements of temperature, humidity and product respiration, and resulted in a 15-20% energy savings and a better quality of the product than fixed-parameter operation. Implementation of GSM-based remote monitoring allowed farmers to get a notification about a failure of the system or unfavorable conditions. Manuwa et al. [19] investigated the material durability and longevity of evaporative cooling systems and performance of the cooling systems during 3-5 years of operation. The minerals deposited and the biological growth reduced the effectiveness of cellulose pads by 15-25% after two years, thus necessitating the replacement or cleaning procedure periodically. Components made of stainless steel and treated aluminum proved to be more durable than galvanized steel which showed corrosion-related failures in high-humidity conditions in no less than 18-24 months.

Kitinoja and Thompson [20] explored the idea of climate-specific design adaptations and came up with customized designs of different agricultural zones. Their study determined that direct evaporative cooling with maximum effectiveness was favored by hot-dry climate (relative humidity below 40) and indirect or desiccant-enhanced cooling was needed in warm-humid climate (relative humidity above 70). Hybrid configurations, which run in variable modes, according to seasonal humidity patterns were beneficial in semi-arid areas. Kabeel et al. [21] were able to investigate recent developments in the use of nanotechnology by examining nanofluid-based evaporative cooling systems. The heat transfer coefficients were 18-25 percent higher and the total cooling efficacy was 12-18 percent higher with addition of 0.5-2 percent by volume of Al 2 O 3 and CuO nanoparticles. Nevertheless, the stability over a long period, the possibility of accumulating nanoparticles, and the cost-benefit ratios have to be researched prior to widespread adoption. The survey indicates that there has been gradual development of simple passive systems to highly advanced hybrid systems that combine several technologies. Regular patterns are the focus on locally-supplied materials, ease of use in resource-constrained situations, and optimization of certain climatic conditions and commodity needs.

3. Methodology

Research Approach and Selection Criteria

The methodology used in this review involved systematic literature review to adhere to PRISMA (Preferred Reporting Items to Systematic Reviews and Meta-Analyses) guidelines to achieve exhaustive and impartial coverage of the pertinent research. The search strategy included various academic databases, such as IEEE Xplore, ScienceDirect, Springer, Wiley Online Library, and Google Scholar, which included publications published between January 2010 and March 2024. Keywords were a combination of solar evaporative cooling, agricultural cold storage, post-harvest preservation, photovoltaic cooling systems, passive cooling and renewable energy storage with Boolean operators to ensure maximum retrieval. Preliminary searches resulted in 347 potentially relevant articles, which were screened using pre-specified inclusion criteria: (1) attention to the principle of evaporative cooling or its application; (2) attention to the preservation of agricultural products; (3) the use of the components of solar energy or renewable sources; (4) the presentation of empirical data or verified modeling studies; (5) publication in peer-reviewed journals or Exclusion criteria were used to remove studies that were purely theoretical without validation, those that dealt with mechanical refrigeration systems without evaporative components and those that did not provide adequate details of methods used to carry out research. Following a methodological screening, 30 high-quality publications were included in the final review corpus which represents a variety of geographical settings, system configurations, and research methodologies.

Data Extraction and Classification Framework

Data elements extracted in the chosen publications covered specification of the system design (cooling capacity, dimensions, materials), performance (temperature reduction, cooling efficiency, COP, energy consumption), as well as economic (capital costs, operational costs, payback periods), environmental (climate classification, ambient temperatures range, humidity levels) and product-specific (shelf-life extension, quality retention, spoilage reduction) outcomes. Four main categories of studies were identified according to the methodology used to cool the product: direct evaporative cooling systems wherein the product-contact air is passed through wetted media, indirect evaporation cooling systems that utilize heat exchangers to separate the process and product air streams, hybrid systems that combine multiple cooling methods or energy sources, and advanced systems that incorporate emerging technologies like desiccants, phase change materials, or nanofluids. Other classification dimensions were energy source (passive solar thermal, active photovoltaic-powered, hybrid configurations), scale of implementation (laboratory prototypes, pilot systems, commercial installations) and geographical context (tropical, subtropical, arid, semi-arid climates). This classification scheme with multiple dimensions made it possible to compare and contrast the results of various research methods and contexts of implementation systematically.

Performance Evaluation Metrics and Analysis Methods

Comparison of performance among studies necessitated that there was standardization of reported metrics to consider difference among experimental conditions and measurement procedures. Key performance measures were cooling efficiency (η) expressed as actual to theoretical maximum temperature drop, coefficient of performance (COP) which is the cooling output to unit energy input, specific cooling capacity (W/m2 of evaporative media) and temperature drop (ΔT) below ambient temperature. Secondary measures included relative humidity preservation within the best possible limits (85-95% in the case of leafy vegetables, 80-90% in the case of fruits), energy use per unit volume (kWh/m 3/day), water use rates (liters/day/m 2 cooling area), and product-specific measurements such as percentage extension of shelf life and quality retention measured against a standardized assessment criterion. The statistical meta-analysis methods were used to combine performance data of various studies, which included weighted standard deviations and mean to determine the normal performance ranges and outliers. Normalization of climate protocols have made reported performance measures appear to be at standard reference conditions (35C dry bulb temperature, 40 percent relative humidity) and allow performance comparisons across studies. The standardization of cost information to 2024 USD equivalents of all cost data through published inflation indices and currency conversion rates made it possible to meaningfully compare the economic viability of various geographical settings and periods. This rigorously methodological process guarantees that the conclusions and recommendations that are drawn through the review are premised on analytical grounds and are strong syntheses of evidence available.

4. Critical Analysis of Past Work

Critical review of the literature shows that there are some strengths, limitations, and gaps in knowledge that inform the future research directions. One of its main advantages is that the experimental validation has been performed under different climatic conditions, where experiments have been conducted in arid Middle East environments [15], tropical Sub-Saharan African environments [17], and subtropical Asian environments [16]. Such geographical diversity offers strong arguments in favor of the adaptability of technology, but uniformity in the formulation of the experimental protocols is not uniform, which makes it difficult to directly compare performances. There are considerable methodological weaknesses in the presence of short-term (24-72 hours) experimental research, which does not provide evidence of long-term performance decline, seasonal variations and maintenance demands, which are essential to practice implementation. It is only three studies [17][19][20] that looked at systems over multi-year returns that showed performance degradation of 15-30% that were not taken into account by shorter studies. This time bias overestimate's reliability and economic viability of the system to a significant degree that may mislead stakeholders about realistic expectations. The literature is biased in terms of technology (direct evaporative cooling systems 63% of reviewed literature) even though this technology is less relevant in humid environments (Gonzalez-Torres et al., 2016) that cover about 40% of agricultural output worldwide. This area of focus generates knowledge asymmetry with indirect and hybrid systems having inadequate research despite having wider applicability to climatic conditions [12]. Moreover, just a quarter of the research considered crops that are sensitive to humidity such as onions, garlic, and grains that need other preservation measures than widely studied tomatoes and salads. Economic models have developed inconsistent methodologies where there are different assumptions on discount rates (5-12%), system lifespan (5-15 years) and cost components included. A few studies [9][11] also avoided such important aspects as water costs, maintenance periodically, and replacement of components, which artificially shortened the payback periods calculated. Also, the cost of labor monitoring and maintenance of the system, which is a major concern to resource-restricted farmers, was not given sufficient consideration as part of most economic evaluations.

The technological challenges of technological integration of photovoltaic power generation and cooling load profiles are under-explored. Most studies assumed that there were continuous cooling needs without consideration of the time difference between peak solar availability (midday) and peak cooling demands (afternoon/evening) or overnight operation needs. The number of studies that included energy storage solutions was only two [13][18] and the results indicated 40-60% efficiency penalties and cost upsurge that fundamentally changes the economic viability calculations. The literature reviewed has shown little regard to the water quality effects on the performance and durability of systems. Dissolved mineral hard water leads to scaling of evaporative media which decreases efficiency by 20-35% in months [19], but no study has examined water treatment strategies systematically. Likewise, biological development (algae, bacteria) of water reservoirs is a hygienic issue and performance deterioration that have not been sufficiently covered by existing studies. The analysis of material selection is geographically biased in favor of commercially viable synthetic materials (cellulose pads, PVC components) without adequate exploration of locally-available options that will be important in terms of sustainability in developing areas. Although there are studies [10][20] that studied natural fibers, extensive durability tests, biodegradability tests, and lifecycle environmental impact comparisons are few. The level of sophistication of control systems differs radically between studies, with some being completely passive control systems to microcontroller-based adaptive algorithms [18]. Nevertheless, the cost-benefit analysis of the complexity of control in relation to the performance gains is rarely found, and practitioners lack evidence-based literature on how to properly choose the technology. The new movement towards IoT integration and remote monitoring does not critically assess the reliability of remote monitoring in rural areas where there are few connectivity infrastructures.

5. Discussion

The overall findings of literature reviewed indicate that solar-powered evaporative cooling systems are feasible and sustainable options to traditional refrigeration in select agricultural settings, but a successful deployment would necessitate a close alignment of technology setup with climatic environments, commodity demands, and socioeconomic environments. It has been shown that well-engineered systems can attain 50-70 percent of the performance of conventional refrigeration systems at 10-20 percent of the capital and operating cost [11][17], which is a reasonable compromise between the resources limited agricultural population and maximum performance. Climate becomes the prevailing phenomenon that determines the choice of system and performance expectations. Hot-dry climates (temperature over32 o C, relative humidity under40 o C) are the most suitable climates in which direct evaporative cooling can be effective with ratios of 75-85 percent and temperature changes of 15-20 o C [14][21]. On the other hand, wet tropical climates need indirect designs or desiccant upgrading and are willing to sacrifice cooling performance (8-12C cutdown) in exchange of the ability to operate throughout the year [16]. Such climate-technology alignment is potentially vital knowledge in implementation planning, but is insufficiently highlighted in practitioner-oriented implementation planning guides. There is a high sensitivity of economic viability to scale, as per-unit costs decrease significantly with larger installations because of the fixed costs of components (PV panels, controllers, structural materials) are divided by larger storage volumes. Capital costs of community-scale cooperative systems (10-20 m 3) are two times less than those of individual household units (1-2 m 3) of $25-35 per cubic meter and $45-60 per cubic meter respectively [17]. According to this principle of economies-of-scale, collective ownership models should receive more research and policy focus in order to increase the accessibility of technology. The difference between laboratory prototypes and field implementations needs to be considered as a technology gap. In the controlled experimental conditions, the real-world performance is systematically overestimated by 20-35 percent because of such factors as inconsistent water quality, inconsistent maintenance, component degradation, and unoptimal operation by the user [19]. It is necessary to address this gap in implementation by placing more emphasis on user-centered design, simplified maintenance guidelines, and a strong training program-sociotechnical aspects have been given less focus on research conducted mainly in the field of engineering.

Also, emerging technological advances such as nanofluid integration [21], phase change materials [13] and intelligent controls [18] exhibit performance gains of 12-25% at cost premiums of 35-60. The cost-benefit ratio of such advanced capabilities is relative, probably reasonable in the case of high-value crops and commercial use but not necessarily in subsistence farming scenarios where affordability and simplicity are demanded. Studies ought to be more explicit on how the technology is appropriate in various types of users as opposed to going to the extreme of ensuring maximum technical performance without considering situational appropriateness. The assessment of environmental sustainability outside the energy consumption is scarce. Sustainability claims would be enhanced with comprehensive lifecycle analyses of water usage (3-8 liters/day/m² cooling area), embodied energy in materials, end-of-life disposal, and biodegradability to provide opportunities of improvement. Replacement of synthetic with natural materials is promising increased sustainability [10][20], but needs to be increased in durability and have standardized performance requirements to become widely adopted.

6. Conclusion

This is a thorough overview of solar driven evaporative cooling systems in agricultural cold storage to show that there is a great deal of technological maturity in certain applications, as well as gaps in knowledge that still need to be addressed through research. The technology has been shown to save up to 35-45 percent of post-harvest losses, up to 200-400 days of shelf life, and offer an economically viable alternative to traditional refrigeration to resource-constrained agricultural populations, especially in hot-dry regions with plenty of solar resources and low humidity. The factors of critical success that have been identified amid the meta-analysis are proper selection of system configuration that fits climatic conditions, proper sizing of capacity that is just enough to support the commodity-specific cooling needs, integration of adequate photovoltaic power and energy storage that will allow operation continuity during the day, the use of robust materials that cannot be degraded by the environment, adoption of accessible maintenance protocols that will be able to meet the local technical. The gaps in primary research that need future research are long-term field performance studies over years and seasons, extensive economic studies to include all lifecycle costs and local economic parameters, systematic study of hybrid and indirect configurations to use in the humid climate, development and validation of locally-sourced, sustainable materials with competitive performance and long life, exploration of advanced control strategies to balance performance gains with cost and complexity increases, water treatment and management procedures to avoid performance decay and maintain hy The road to mass implementation needs to take interdisciplinary methods that combine engineering creativity with economic thinking, social science information, and policy implementation systems. Design guidelines, performance testing protocols, and quality certifications should be standardized to boost the credibility of the technology and support the development of the market. Demonstration projects and capacity-building initiatives, as well as financial systems (subsidies, microfinance, cooperative procurement) may be faster and more effectively propagated to smallholder farmers who need post-harvest assistance the most. Developed and installed solar-powered evaporative cooling systems have significant potential in developing sustainable agricultural systems, food security, and rural livelihoods across the developing regions of the world.

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