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RESEARCH PAPER **MECHANICAL ENGINEERING**

System-Level Energy Distribution Study of a Renewable Agricultural Microclimate System

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ABSTRACT

A comprehensive analysis of the total energy distribution within an integrated design for sustainable agricultural production in coastal climatic conditions. The system configuration consists of evacuated tube collector, absorption cooling system, thermal energy storage, solar still, and greenhouse operating on humidification-dehumidification principles, provides a fundamental model for evaluating energy flow and utilization of the interconnected subsystems. Thermodynamic modelling, based on energy and mass balance along with inverse technique of Levenberg-Marquardt method, evaluates greenhouse temperature, vapor pressure deficit, and overall performance under varying solar irradiance between 275–972 W/m^2 for typical ambient conditions of Indian coastal-areas. The obtained results presented, stable internal temperatures of 24–28°C and relative humidity of 60–90%, with VPD maintained in the optimal 0.5–1.2 kPa range for crops such as tomatoes and cucumbers by optimizing air (60–90 kg/s) and water (≥0.7 kg/s) mass flow rates. The greenhouse system demonstrates that 90% evapotranspiration water recovery, continuous year-round operation without fossil fuels, and enhanced concentration yield (~1 m^3/day per 100 m^2) attained through the heat integration. The integrated design addresses, key challenges using groundwater/saline agriculture with water scarcity, overheating, and energy intensity for minimizing the energy losses and enabling scalable, low emissions in food production.

Keywords: Solar-energy, Greenhouse, Thermal analysis, Sustainable agriculture, Coastal climatic conditions, Thermal energy storage

In recent times, the water scarcity is one of the most challenging problems especially in dried and semi-dry regions where the demand of the supplies has been exceptional at a startling percentage. Over the

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last decades, global water usage has been doubled than the rate of population growth, resembles in the production of the agriculture output was holding the brunt of this strain. In this context, farming has consumption of roughly 70% of the world's freshwater, making the process for more efficient water management not just for a necessity but also for the survival of the food security. Arid/Dry zones, which has presence of about 40% of the land surface on the earth that includes,the hot dunes of the Arabian Peninsula to the dehydratedareas of North Africa that aggravate the issues related to availability of water resources. The farmers contend with not only limited rainfall but also saline groundwater, which was used for irrigation that salinize the soils and reduce long-term productivity of the crops[1-4]. With including all the conditions, the extreme environmental temperatures that often exceeding 45°C have intense solar radiation that accelerates evaporative conditions that results in low humidity levels that stress the crops, leading to less yielding production that are 30–50% lower than the normal temperate areas.

Traditional open-field agriculture relies heavily on fossil fuel-powered pumps and irrigation systems, that contribute significantly to greenhouse gas emissions that increasingly unsustainable in agriculture and responsible for about 24% of global greenhouse gases. Moreover, these practices are helpless to climate variability, results in shortening of the crop seasons and inconsistency in harvesting that loom economic stability for rural communities. Henceforth, to protect the cultivation systems such as greenhouses have gained importance as a pathway to resilient, for low-emission food production. With maintenance of a controlled micro-environment, greenhouses can increase its crop yield nearly by 10–20% with reduction in water and energy usage by 30% as compared to conventional methods[5-9]. The institution of greenhouses will protect against high temperature conditions, insects or pests, excessive evapotranspiration that allows the crops extended for year-round cultivation of high required crops such as tomatoes, cucumbers, and bell peppers.

Establishing the greenhouses in high dried regions that extant the climatic conditions which represent its own set of complications. Maintaining the optimal conditions ranging from 18–30°C for temperature and 60–90% of relative humidity (RH) for most of the vegetable crops involves substantial energy inputs and particularly to maintain lower temperatures during peak summer months. Extended temperatures that are above 35°C induces higher heat stress in plants resulting in reduction of photosynthesis and output quality of the crops, where higher RH conditions can lead to fungal diseases or presence of excessive transpiration extends to lifelessness. The system process of natural ventilation reduces rapidly when outdoor temperature increases as the crops are unable to handle heat buildup[10-13]. The arrangement of nets or screens helps in reduction of the irradiance, whereas has the limitation for the photosynthesis, which is critical fragment for the crop growth. The provision of evaporative cooling system provided with fans and wet pads resist the higher temperatures by converting sensible heat into latent heat through water evaporation. However, the effectiveness of the system decreases in peak summerwhere ambient RH rises to some extent, uplifting the wet-bulb temperature that results in marginal cooling conditions between 5–10°C below ambient the temperatures[14,15].

To improve in the performance of the system, vigorous mechanical systems like heating, ventilation, and air conditioning (HVAC) are essential and also this system requires a high energy which are generally produced by fossil fuels in off-grid or from remote areas. Thid leads to increase in the operational costs and also preserves carbon emissions that challenges the sustainability goals to protect agricultural conditions. In this context, the integration of renewable energy arises as a logical correctness and thermal technologies aligning in waterless climatic conditions provides abundant heat source for both desalination and cooling of the system. The integration of greenhouses with desalination processes having dual benefits of turning waste heat into freshwater creation and evaporative cooling. Humidification-dehumidification (HDH) desalination works on water cycle that humidifies air with evaporated saline water and in later stage condensing processstances for its simplicity and adaptability. When the HDH system rooted in a greenhouse, it utilizes the evaporation of saline water for heat absorption and during the condensation process practices for the crop irrigation that completes the loop on water convention[14-18]. Submissive devices like Solar stills that harness sunlight to distilled water through evaporation and/or condensation to enhance the synergy by attaching directly into design of the greenhouse structure, such as the roof in order to filter excess infrared radiation.

Recent studies suggest that the potential of the hybrid system integration in to the greenhouses has been increased. Goosen *et al.*[19] developed a thermodynamic model for the HDH-greenhouse in more dry regions, suggest the prescribed size of GH intensely stimuli the freshwater yields that produces the larger structures nearly three times higher than the concentration. However, the numerical study emphasized the summer overheating as a persistent blockade which compelling the operational breaks. Zamen *et al.*[20] suggested the incorporation of efficient solar heaters, results in attaining 6–22 m^3/day in a 500 m^2 facility though high ambient RH with reduction in cooling efficacy. The circulation of fluid passing through the roof of the greenhouse, where ground/saline water circulates through the double layered coverings shown a reliable load reduction. The partial solar absorption for the evaporation, while Abdel-Ghany *et al.*[21] reported a temperature drop in field nearly by 5°C in aired dry conditions.

Mahmoudi *et al.*[22] developed a prototype for solar-wind powered seawater greenhouse in gulf countries produces a yielding of 297 L/day without using fossil fuels where the exergy inefficiencies were observed for intermittence. Sajid and Bicer[263] employed nanofluid based photovoltaic thermal (PVT) roofs in an inclusive design shown drop of cooling demands by 26% through selective spectrum absorption. Several authors reported the inclusion of light splitting solar stills by Mamouri *et al.*'s[24] resolved the 85% of tomato irrigation requirements, where Rabhy *et al.*[25] transparent roof distillers were improving 37.5% of water requirements while cutting the energy usage by 60%. Mahmood and Al-Ansari[26] modelled an HDH based solar greenhouse distributing 17.5–27.3 m^3/day in conjunction with minimal micro-climatic conditions that emphasizes the role of absorption chillers for stability. Many of the research studies focused on the moderate or coastal areas with suitable crop conditions by overseeing the interior aridity[27]. Dry-conditions prototypes or designs often depend on water intensive evaporative pads or fossil supplements having a limited runtime of 8 to 9 months and enhancing of the production costs[28-30]. The integration of thermal storage to variation of solar radiation or to measure exergy losses in coupled HDH systems[31-33]. However, evapotranspiration recovery of recirculating water and plant transpired water is unexplored by many authors depending on adaptability of specific crops counting geographies.

The present research study addresses the existing gaps with an innovative, entirely solar-powered greenhouse designed for extremely dry conditions, such as those found in arid /coastal areas. The structure integrates a double-glazed roof that serves as a solar still, capturing approximately 20% of incoming sunlight (usually between 250–1000 W/m^2) to desalinate saline groundwater while providing shade for the canopy. The heated brine progresses the evaporation rates of humidified air, resulting in higher overall outputs. A combination of an evacuated tube collector (ETC) and thermal energy storage (TES) powers water absorption cooling system, which supplies chilled brine to condenser that collect condensate and maintain a temperature of 18–30°C and relative humidity of 60–90% throughout the year. In contrast to earlier models, this system recovers more than 90% of water lost to evapotranspiration, operates continuously without additional cooling support, and exclusively utilizes saline feedstocks eliminating the need for freshwater resources. Thermodynamic modelling through first and second law evaluations confirms efficiency during seasonal changes in dried/coastal regions (utilizing TMY3 data [34,35]), focusing on crops such as tomatoes (optimal at 20–30°C[36]) and cucumbers (25–30°C[37]). This study promotes scalable, zero-emission agriculture by showcasing the cooling capacity using the inverse techniques to estimate the temperatures and VPD for freshwater water supply within a 1,000 m^2 enclosure. It guarantees economic sustainability by maintaining continuous operations and provides a model for areas with limited water, promoting food independence despite climate challenges.

Methodology

The methodological approach for estimating the temperature conditions for the greenhouse from conceptual design with ensuring a rigorous, replicable trail to assessing the proposed system's feasibility has been discussed in the section. The emphasis has been considered for transparency in model formulations and parametric evaluations to facilitate future adaptations.

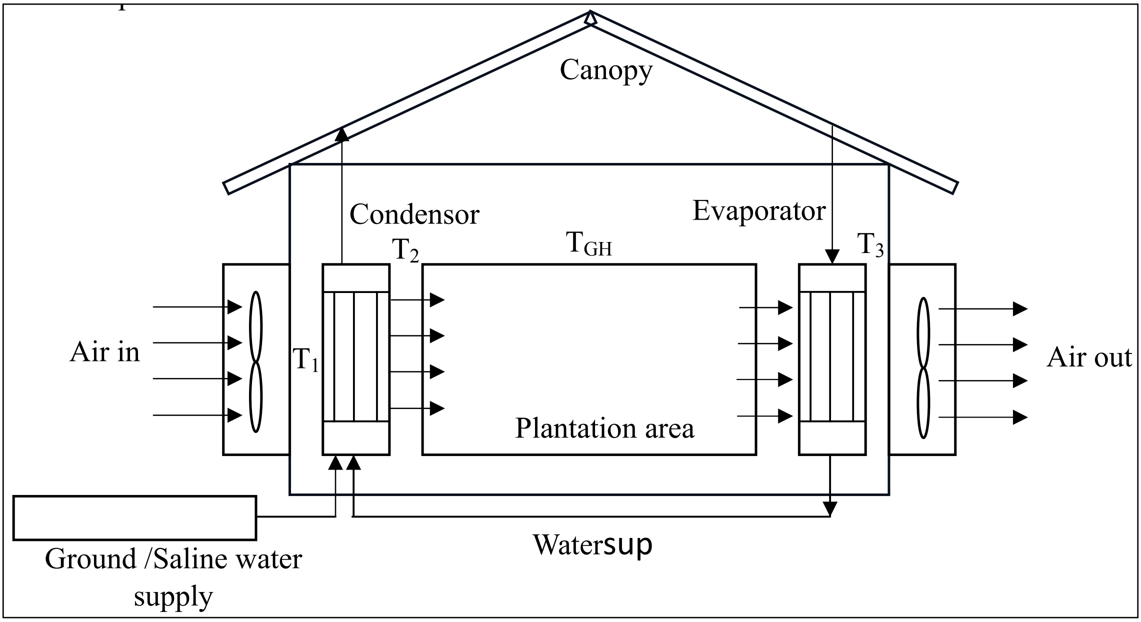

Fig. 1: Representation of the renewable energy driven greenhouse

The system of the engineering process for the greenhouse establishment is illustrated in Fig. 1. The estimation of the temperature conditions have been furnished for the dimensions of the greenhouse for 100 m^2 floor area, 50 m length × 2 m width, polyethylene covering with a feasible heat transfer coefficients ($U = 5\text{-}7 W/m^2 \cdot K$[38]), for the cultivating crop of tomatoes with leaf area index (LAI = 3–4), for the temperature range of 20–30°C with deliberation of relative humidity (RH = 60–90%[39]) through maintaining mechanical cooling efficiency and collector type of ETCs for high-temperature output up to 473 K at 60% efficiency[40, 41].

Groundwater or saline water serves as the primary input of the water system which is passed through the condenser before entering to the greenhouse (8–10°C) and the water supply is routed through the roof solar still. The canopy a double-pane glass assembly (emissivity $\varepsilon = 0.88$, transmissivity $\tau = 0.75$[42,43]) absorbs approximately 20% of beam irradiance, and conducted heat through the circulated water at 50–60°C for distillate collection while transmitting photosynthetically active radiation (PAR, 400–700 nm) to the system. Preheated seepage enhances HDH humidification, targeting specific humidity conditions. Airflow, fan-driven at $\dot{m}_{air} = 0.1–1$ kg/s, flowsthroughthe condenser(UA = 500 W/K[44]), yielding ~1 m³/day initial condensate for irrigation storage. Passing through the canopy itadvances the sensible/latent heat from evapotranspiration ($E_\lambda = 300–1500$ W/m²)[45] before passes through the evaporator contact and exit to the ambient conditions for the total harvest. Electricity for the auxiliaries such as fans, pumps shoulderfor the photovoltaic supplementation or grid associationto minimize the thermal needs for the continuous working conditions of the system[46-49].

Estimation of greenhouse temperature

The temperature of the inlet air reduces when passes through the condenser at the entry into the canopy area of the plantation. The air enters with the lower temperature conditions varies while roving through the plantation area leads to increase in temperature and water vapor in the form of evapotranspiration and the water balance of the canopy is followed as[50-53]:

$$\dot{m}_{A2} \times \omega_2 + \dot{m}_{Evapotranspiration} = \dot{m}_{A3} \,.\, \omega_3 \qquad \ldots(1)$$

The energy balance of the greenhouse is given as follows:

$$\dot{m}_{A2.}\, h_2 + \dot{m}_{Evapotranspiration}.h_{GH} + \dot{Q}_{GH} = \dot{m}_{A3} \,.\, h_3 \qquad \ldots(2)$$

Where, $\dot{m}_{Evapotranspiration}$ is the amount of water vapor present in the plantation region,

$$\dot{m}_E = ET \times A_{GH,Canopy}, \text{ Where, } ET = \frac{E_\lambda}{h_{fg}} \qquad \ldots(3)$$

$$E_\lambda = \frac{\delta . R_n + \left(\frac{2.LAI.\rho_\alpha C_p}{r_e}\right)(VPD)}{\gamma\left(\left(1+\frac{\delta}{\gamma}\right)+\left(\frac{r_i}{r_e}\right)\right)} \qquad r_i = 200\left(1+\frac{1}{e^{(0.05.(\tau_{cover}.I_S-50))}}\right).\frac{RH_{GH}}{100}$$

$\dot{Q}_{GH}$ is the total amount of heat generated from the greenhouse explained as follows:

$$\dot{Q}_{GH} = \dot{Q}_{Sun} + \dot{Q}_{cover} \qquad \ldots(4)$$

where $\dot{Q}_{Sun} = \tau_{cover} \times I_s \times A_{Floor,\,GH}$ and $\dot{Q}_{cover} = U_{cover} \times A_{Surface,\,GH} \times (T_A – T_{GH})$

By equating the equations 1 and 2, and provided with the necessary equations to energy balance. Hence, the equations are rearranged and formed to the unknown parameters in the equation and it followed as:

$$1005 \times T2 \times \dot{m}_A + 1880 \times T_2 \times \dot{m}_A \times (\omega_1 + /\dot{m}_A) + \dot{m}_E.h_{gh} + \dot{Q}_{GH} - 1005 \times T_{GH} \times \dot{m}_A - 25 \times 10^2 \times \dot{m}_E - 1880 \times T_{GH} \times \dot{m}_A \times (\omega_1 + / \dot{m}_A) - 1880 \times T_{GH} \times \dot{m}_E = 0$$

With assumption of the inlet temperature of the greenhouse (T2), the temperature of the green house for the particular solar radiation can be estimated using the Levenberg-Marquardt method[54-56].

The maximum vapor pressure can be hold by the air passing through the plantation area for the particular temperature conditions during the evaporation process is presented as follows

$$\text{Vapor Pressure Deficit (VPD)} = P_g - P_v (\text{kPa}) \qquad \ldots(5)$$

where, P_g is the Saturation vapor pressure and P_v is the Air vapor pressure and relative terms expressed as shown in below equations;

$$P_g = 0.61121 * \exp\left(18.678 - \frac{T_{gh}}{234.5}\right)\left(\frac{T_{gh}}{257.14 + T_{gh}}\right) \quad P_v = P_g * RH_{gh} \qquad \ldots(6)$$

The air temperature moving through the greenhouse rises after it passes through the canopy zone, while the decrease in relative humidity is observed. Hence, the air retains the capacity to hold moisture, an evaporator is placed after the canopy to raise the relative humidity. The solar still provides heated with the necessary water supply to the evaporator.

RESULTS AND DISCUSSION

The estimation of an acceptable operatable temperature of the greenhouse for the respective mass flowrates of the air/water and the relative change in temperatures along the daylight heat rate Q_{Sun} in consideration of variation in relative humidity conditions were demonstrated using the inverse techniques. Primarily, the variation of the vapour pressure deficit (VPD) to the suitable temperature conditions of greenhouse (TGH) for varying relative humidity conditions were presented in the Fig. 2(a). With increase in the temperature, the increase in VPD is observed, whereas with increase in RH of the air the significant reduction in the VPD is evident. Hence, the mass flow of the air entering the greenhouse and the relative RH conditions that certain the possible estimation of the temperature conditions of the greenhouse.

In general, the power consumption of the fan required for the flow rate of the air to extent of pressure drop is subjected to efficiency of the fan to maintain the air and water flow conditions of the green house. As VPD depends on both saturation pressure for water (*Pg*) and water vapor pressure in the air (*P*v), VPD is a function of relative humidity and temperature. Low water flow increases the temperatures, which leads to higher TGH, which is considered as the average of temperatures of inlet and outlet. Similarly, the relative humidity decreases which reduces the water vapor partial pressure. Therefore, low water flow rates result in higher VPD's as the difference between *Pg* and *P*v increases. As mentioned, a VPD between 0.5 kPa and 1.2 kPa is deemed ideal for tomato growth.

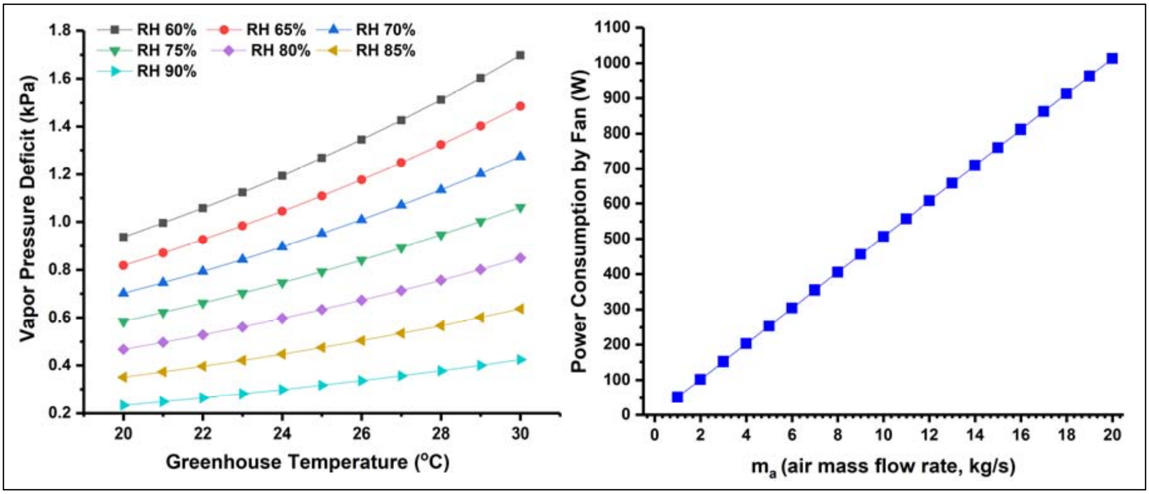

Fig. 2: (a) Variation of VPD for the relative humidity conditions for the greenhouse temperatures, **(b)** Power consumption required for the fan to maintain certain mass flow rates for the greenhouse

To a warmer inlet temperature, a higher Q_{Sun}, increases the overall temperature in the greenhouse across the whole air flow range drastically drops the necessary airflow to maintain *VPDGH*. Simultaneously, the humidity RHGH decreases. However, this will result in a significant increase in greenhouse temperature. Greenhouses rely on a steady climate for their plants. High water throughput is also a goal of the current system to maximize drainage water and salt disposal. Rather than reducing air flow, water flow rate can be increased to operate at the desired *VPDGH* while maintaining lower greenhouse temperatures. In order to maintain the necessary airflow and/or the water flowrates for maintaining the suitable temperatures in the greenhouse by equating the thermodynamic and evaporation model equations into a temperature based unknown equation for estimating the necessary temperature and VPD using the Levenberg-Marquardt method. The results for the heat generation of the sun at three different time instants for solar radiations of Q_{Sun} = 275, 972 and 500 W/m^2 comparatively at the atmospheric temperatures of 28°C, 34°C and 29°Cfor the coastal regions of the India[57].

The estimated temperatures and the vapor pressure for the variation of mass flowrates of air and water for three different solar radiance are shown in Fig. 3. As, the water flowrate conditions are at lower capacity for the GH system, with increase in the flowrate the reduction in temperature is evident from all the given conditions as presented in results for higher mass flowrates of the air. For instance, to maintain the greenhouse at temperature of 26°C for a proper yield of the plantation throughout the day time, the greenhouse should be given constant input of mass flowrate of water at 0.7 kg/s and as the temperature is increasing the fan speed should be maintained within the range varying from 60-90 kg/s and contrariwise for the airflow system. The estimated data useful for the year-wise variation of the ambient conditions and accordingly adjusting for the required air and water flowrates of the greenhouse system. The analysis also showed that a better understanding of the inner workings of a greenhouse is needed. Currently, the range of solar intensity used in the model is at higher end of the solar radiation and depending on the measurement error with intensity of Q_{Sun}, the system could either be operating far beyond the acceptable range of VPD or exactly within the system range.

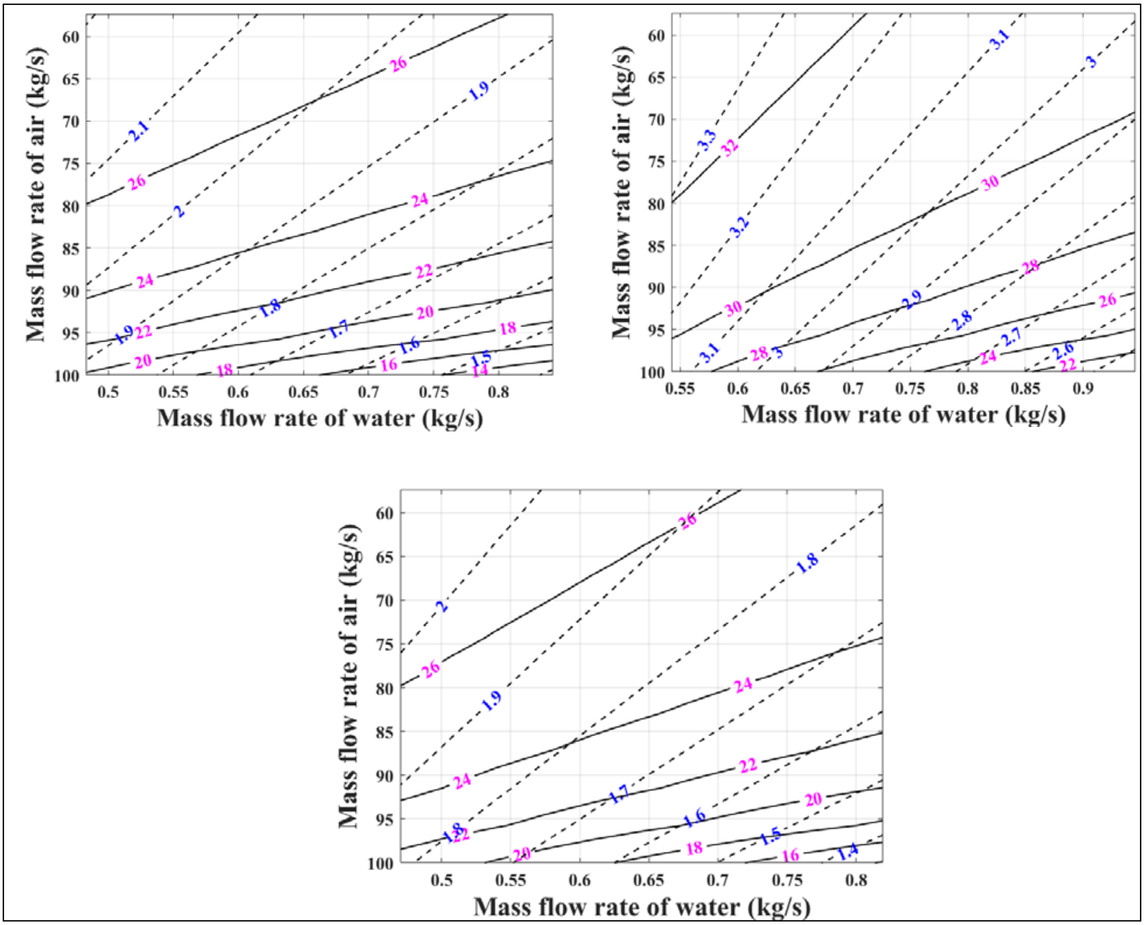

Fig. 3: Comparison of temperature fields with the vapor pressure deficit at different solar radiations **(a)** 275W/m^2 **(b)** 972 W/m^{2}and **(c)** 500 W/m^2.

For optimum operation condition, low airflow rate and high-water throughput are desirable. This would keep the cost for the fan low and allow farmers to maximize the usage of their drainage water. However, exact predictions of actual operating conditions are difficult, as the sun intensity varies with location and time throughout the day. An adaptive system that automatically regulates the water input to maintain a specific air flow and VPD is the best way to compensate for those changes. The models also serve to guide design of the cooling systems how that the footprint required by the evaporation chamber is mostly influenced by the droplet size. As larger droplets require longer estimated evaporation time, the footprint needs to be bigger to slow down the air stream and provide sufficient resident time. It can be seen that changes in inlet humidity and temperature have a minuscule effect on evaporation time and have significant results in obtaining the crop yields.

The current work presents the theoretical modelling for stable microclimatic conditions for the crop system. Future efforts should prioritize establishing the long-term testing of scaled prototypes (e.g., 100–500 m²) under actual coastal climatic conditions either in coastal and/or dry regions. This will extent invalidation of the model predictions and quantify real evapotranspiration recovery rates across crop cycles of tomatoes and/or cucumbers. Furthermore, it assesses the comprehensive techno-economic analysis and life cycle assessments for the component deprivation such as fouling, solar still scaling with saline feed, measurement of year-round performance of the green house. The real-time adaption and development of model predictive control (MPC) algorithms that dynamically adjust air/water flow rates, fan/pump speeds, and thermal energy storage discharge based on forecasted irradiance conditions will optimize the energy usage and maximize the yield stability of the crops. High water recirculation is a significant strength for the maintenance of the green house, but brine concentration increases along with the time. Hence, future works should also address,the insights of zero-liquid-discharge (ZLD) strategies and salt crystallization for the industrial usage.

CONCLUSION

Thepresent study demonstrates the thermodynamic analysis and simulation-based evaluation of a fully renewable energy supported greenhouse model for higher temperature climatic conditions near coastal regions. The integration of the systems of evacuated tube collectors (ETC), thermal energy storage (TES), an absorption cooling system (ACS), a double-glazed roof solar still, the proposed configuration achieves stable year-round microclimate control conditions for the greenhouse and minimizing the usage of energy inputs. The results establishes that the system effectively maintains greenhouse air temperatures in the suitable yielding range of 22–28°C and with a relative humidity of 60–90% for high-value crops like tomatoes and cucumbers, even under high solar irradiance (up to 972 W/m^2) and ambient temperatures exceeding 34°C. Vapor pressure deficit (VPD) can be reliably controlled within the ideal range of 0.5–1.2 kPa by adjusting air mass flow rates (60–90 kg/s) for the water flow rates $\geq$0.7 kg/s. The higher water convention preferred for lower energy consumption and better conservation of the system. The condensation of the air flow and evapotranspiration recovery enable over 90% of the water recirculation that significantly reducing the freshwater demand and enhancing the usage of hard water which yields compared to conventional systems.

The unknown parameter analysis deliberates the greenhouse robustness that the lower temperature water flowing through the condenser and evaporator, coupled with preheated groundwater/brine from the solar still. The system effectively moderates overheating while employing the waste heat streams for increased concentrate production (~1 m^3/day initial condensate for a 100 m^2 greenhouse). The implementation of inverse modelling (Levenberg-Marquardt method) provides a practical tool for predicting greenhouse temperatures and optimizing flow rates under varying solar radiation and ambient conditions. The methodology for estimation of temperature conditions according to the modification of mass flowrates of air/water comforts the solving of the thermodynamic and evaporation models. As a result, an estimated evaporation chamber footprint can be predicted per 100 m^{2}of GH. A higher area of GH’s can be cooled by a system that ranges by the duplication factor of the desired system. The size marginally changes if different inlet conditions are provided and serve as guidance rather than absolute required size. More accurate information regarding the solar intensity will narrow the size range even further. Parametric insights guide practical implementation, including evaporation chamber sizing and adaptive flow control, offering a viable framework for resource-constrained regions.

REFERENCES

1. UNESCO, 2021. World Water Development Report 2021: Valuing Water as an Economic Good. United Nations Educational, Scientific and Cultural Organization, Paris.

2. FAO, 2022. The State of Food and Agriculture 2022: Leveraging Automation in Agriculture for Transforming Agrifood Systems. Food and Agriculture Organization of the United Nations, Rome.

3. Qureshi, A.S., McCornick, P.G., Qadir, M. and Aslam, Z. 2010. Managing salinity and water logging in the Indus Basin of Pakistan. *Agric. Water Manag.,* **97**: 1233–1240.

4. IPCC, 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

5. Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Marland, G., Rounsevell, M., Shen, Y. and Thonicke, K. 2014. Agriculture, forestry and other land use (AFOLU). *In:* Edenhofer, O. (Ed.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 811–922.

6. Lamnatou, C., Flores, J.D.S. and Chemisana, D. 2020. Solar thermal desalination: A literature review with bibliometric analysis and future perspectives. *Renew. Sustain. Energy Rev*., **118**: 109512.

7. Ahamed, M.S., Chetia, S., Tan, C.S., Trudell, G., Haddad, S., Brewer, W. and Mohammadi, H. 2020. Energy use in Canadian greenhouse production: A meta-analysis. *Renew. Sustain. Energy Rev.,* **123**: 109778.

8. Vadiee, A. and Martin, V. 2013. Energy management strategies for greenhouses: A comprehensive review. *Renew. Sustain. Energy Rev.,* **26**: 83–95.

9. Sethi, V.P. and Sharma, S.K. 2007. Survey of cooling technologies for worldwide agricultural greenhouse applications: A technical update. *Sol. Energy,* **81**: 1441–1450.

10. Shamshiri, R.R., Jones, J.W., Thorp, K.R., Ahmad, D. and Dragičević, Ž. 2018. Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: A review. *Artif. Intell. Agric*., **2**: 1–14.

11. Katsoulas, N., Bartzanas, T. and Kittas, C. 2019. Microclimatic effects on crop performance in protected cultivation systems. *Biosyst. Eng.,* **188**: 109–121.

12. Peyman, M., Mousavi, S.M. and Hosseini, S.M. 2021. Optimization of greenhouse design for sustainable agriculture: A review. *J. Clean. Prod.,* **312**: 127789.

13. Ntinas, G.K., Varras, G., Bantis, F. and Koukounaras, A. 2019. Comparative study of greenhouse microclimates under different cooling systems: A case study in Greece. *Biosyst. Eng.,* **181**: 37–50.

14. Kabeel, A.E., Abdelgaied, M. and Essa, F.A. 2019. Recent progress in solar stills: A comprehensive review. *Renew. Sustain. Energy Rev.,* **105**: 35–51.

15. Sharshir, S.W., Peng, G., Wu, L., Essa, F.A. and Kabeel, A.E. 2017. Enhancing the solar still performance using internal and external reflectors. *Appl. Therm. Eng.,* **114**: 154–166.

16. Ghaffour, N., Missimer, T.M. and Amy, G.L. 2017. Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination,* **413**: 81–91.

17. Al-Ansari, T., Pottie, D. and Schfer, A.I. 2020. Integrated water resources management for sustainable food production in arid regions. *Energy Convers. Manag.,* **224**: 113312.

18. Panchal, H., Sadasivuni, S.A., Patel, N. and Thakkar, H. 2019. A review on solar desalination with integrated solar still and multi-effect distillation. *Groundw. Sustain. Dev*., **9**: 100228.

19. Goosen, M.F.A., Sablani, S.S., Al-Hinai, H., Al-Obeidani, S., Al-Belushi, R. and Jackson, D. 2003. Fouling of reverse osmosis and ultrafiltration membranes: A critical review. *Sep. Sci. Technol.,* **39**: 2261–2297.

20. Zamen, S., Soufari, S.M., Vafaei, S. and Abbasi, A. 2009. Experimental investigation of a two-stage humidification–dehumidification desalination system heated by a solar flat plate collector. *Desalination,* **247**: 324–331.

21. Abdel-Ghany, A.M., Al-Helal, I.M. and Shady, M.R. 2011. Human thermal comfort and heat stress in an arid climate: A case study in the greenhouse cultivation of tomato. *Sol. Energy,* **85**: 3135–3145.

22. Mahmoudi, A., Darwish, N.N. and Al-Namlah, A. 2010. Seawater greenhouse in Oman: A sustainable solution to water scarcity. *Desalination,* **251**: 29–36.

23. Sajid, M. and Bicer, A. 2022. Integration of nanofluids in a multi-generation system for sustainable greenhouse applications. *Energy,* **239**: 122397.

24. Mamouri, M.M., Kalantar, Z. and Esfahani, R.T. 2014. Experimental investigation of light effects on the performance of a solar still coupled with a greenhouse. *Energy Convers. Manag*., **78**: 665–672.

25. Rabhy, M., Sharshir, S.W. and Abdelrahman, A. 2016. Experimental study of a solar still with transparent distiller integrated into a greenhouse roof. *Energy Procedia,* **93**: 228–235.

26. Mahmood, F. and Al-Ansari, T. 2021. Solar-driven humidification-dehumidification desalination for greenhouse cooling: A thermodynamic analysis. *Energy Convers. Manag*., **227**: 113456.

27. Al-Mutaz, I.S. and Al-Ghunaimi, A.A. 2014. Desalination in arid regions: Challenges and opportunities in the Gulf. Desalin. *Water Treat.,* **52**: 4567–4574.

28. Duffie, J.A. and Beckman, W.A. 2013. Solar Engineering of Thermal Processes, 4th ed. John Wiley & Sons, Hoboken, NJ.

29. Farahat, S., Halawa, E. and Perera, F. 2004. Building integrated photovoltaic thermal solar collectors for hot climates. *Energy Convers. Manag.,* **45**: 1683–1697.

30. Stanghellini, C. 1993. Evapotranspiration in greenhouses: Measurements and simulations. *Acta Hortic*., **328**: 25–34.

31. Sabiha, M.A., Saidur, R. and Said, Z. 2015. Energy performance analysis of LPG cooking appliances using different fuels. *Renew. Sustain. Energy Rev*., **51**: 363–373.

32. Kenisarin, M. 2010. A comparative review of the effect of PCM encapsulation on the thermal performance of solar energy applications. *Renew. Sustain. Energy Rev.*, **14**: 540–559.

33. Al-Alili, A., Islam, M.D. and Kubo, I. 2014. Vacuum membrane distillation desalination of saline water using solar energy. *Appl. Energy,* **126**: 133–143.

34. Aphornratana, S. and Eames, I.W. 1995. Thermodynamic analysis of absorption refrigeration cycles using a new working fluid pair. *Int. J. Refrig.,* **18**: 244–250.

35. NREL, 2023. National Solar Radiation Database (NSRDB). National Renewable Energy Laboratory, Golden, CO.

36. Monteith, J.L. and Unsworth, M.H. 2013. Principles of Environmental Physics: Plants, Animals, and the Atmosphere, 4th ed. Academic Press, London.

37. Arin, L., Balbontín, M. and Mena, J. 2015. Greenhouse microclimate control for tomato production. *Acta Hortic.,* **1085**: 239–244.

38. Klein, S.A. 2022. Engineering Equation Solver (EES) Professional V12. F-Chart Software, LLC, Madison, WI.

39. ASHRAE, 2021. ASHRAE Handbook of Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

40. Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization, Rome.

41. Tiwari, G.N. and Tiwari, A. 2010. Performance evaluation of a single basin solar still: An experimental study. *Sol. Energy,* **84**: 924–930.

42. Omara, Z.M., Kabeel, A.E. and Younes, M.M. 2015. Enhancing the stepped solar still performance using internal reflectors. *Renew. Sustain. Energy Rev.,* **50**: 823–854.

43. Kalogirou, S.A. 2004. Solar thermal collectors and applications. *Prog. Energy Combust. Sci.*, **30**: 231–295.

44. Cabeza, L.F., Castell, A. and Barreneche, C. 2011. Materials used as PCM in thermal energy storage in buildings: A review. *Renew. Sustain. Energy Rev.*, **15**: 1675–1695.

45. Kim, D.S., Infante Ferreira, C.A., 2008. Solar refrigeration options – a state-of-the-art review. *Appl. Therm. Eng.,* **28**: 574–584.

46. Dincer, I. and Rosen, M.A. 2013. Exergy: Energy, Environment and Sustainable Development, 2nd ed. Elsevier, Oxford.

47. Koutaiba, A., Alami, M. and El Qarnia, H. 2020. Experimental study of a humidification-dehumidification desalination unit integrated with a greenhouse. *Desalination,* **481**: 114379.

48. El-Agouz, S.A., El-Ghonemey, A.A.H. and Ammar, M.H. 2021. A comprehensive review on solar desalination systems. *J. Clean. Prod.,* **290**: 125782.

49. Mahmood, F. and Al-Ansari, T. 2022. Multi-generation solar-powered greenhouse for arid regions: Energy and exergy analysis. *Energy,* **239**: 122109.

50. NREL, 2023. Typical Meteorological Year 3 (TMY3) Dataset. National Renewable Energy Laboratory, Golden, CO.

51. Ntinas, G.K., Varras, G., Bantis, F. and Koukounaras, A. 2019. Comparative study of greenhouse microclimates under different cooling systems: A case study in Greece. *Biosyst. Eng*., **181**: 37–50.

52. Omara, Z.M., Kabeel, A.E. and Younes, M.M. 2015. Enhancing the stepped solar still performance using internal reflectors. *Renew. Sustain. Energy Rev.,* **50**: 823–854.

53. Kenisarin, M. 2010. A comparative review of the effect of PCM encapsulation on the thermal performance of solar energy applications. *Renew. Sustain. Energy Rev*., **14**: 540–559.

54. Aphornratana, S. and Eames, I.W. 1995. Thermodynamic analysis of absorption refrigeration cycles using a new working fluid pair. *Int. J. Refrig.,* **18**: 244–250.

55. ASHRAE, 2021. ASHRAE Handbook of Fundamentals: Psychrometric Charts. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

56. Deen, W.M., 1998. Analysis of Transport Phenomena, Oxford Univ. Press, New York, pp. 132–207.

57. Dash, S.K., Jenamani, R.K., Kalsi, S.R. and Panda, S.K. 2007. Some evidence of climate change in twentieth-century India. *Climatic Change,* **85**(3): 299-321.