Performance Evaluation of single slope solar still by the inclusion of Palm Flower powder and micro Phase Change Material (mPCM) for the enhancement of productivity

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**Performance Evaluation of single slope solar still by the inclusion of Palm Flower powder and
micro Phase Change Material (mPCM) for the enhancement of productivity**

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Abstract:

The objective of the work is to investigate the single slope solar still for the enhancement in productivity by the inclusion of optimum weight of palm flower powder of micro-sized in the absorber basin and optimum weight% of micro-Phase Change Material (mPCM) under the absorber basin. In this regard, the effect of different weights of palm flower powder such as 10, 30, 45, 50, 55, 70, 100, 120 and 150 g in the absorber was analysed. The solar still with 50 g of palm flower powder in the absorber increased the productivity by 37.25 % whereas, for 10, 30, 45, 55, 70, 100, 120 and 150 g were 11.85, 24.78, 36.1, 36.8, 34.35, 33.05, 10.25 and -20.22 % respectively. The effect of different weight% of micro-sized palm flower powder such as 5, 10, 15 and 20 wt%, in paraffin wax, was investigated. The paraffin wax with 20 wt% of micro-sized palm flower powder has a better thermal conductivity of 0.33 W/mK. The experimentation was carried out with 50 g of micro-sized palm flower powder in the absorber basin and 20 wt% mPCM under the absorber basin solar still (PCMPFP-SS) and Conventional Solar Still (CSS). The overall yield of PCMPFP-SS was 4670 ml/m²-day on day 1 and 4250 ml/m²-day on day 2, for CSS it was 3030 ml/m²-day on day 1 and 2800 ml/m²-day on day 2. It was evaluated that the Cost per Litre of PCMPFP-SS was \$ 0.025 and \$ 0.032 for CSS.

Highlights:

- The optimum weight of micro-sized palm powder was 50 g for higher productivity.
- The optimum weight% of micro-sized palm powder in the PCM was 20 wt%.
- The value of thermal conductivity for mPCM was 57.14 % higher than PCM without microparticles.
- The increase in productivity of PCMPFP-SS was 54.12 % on day 1 and 51.78 % on day 2.
- The Cost per litre of PCMPFP-SS was decreased by 33.33 %.

Keywords: palm flower powder; micro Phase Change Material, thermal conductivity, enviro-economic analysis, solar still

U	Uncertainty
A	Accuracy
d_f	Final distillate value
d_i	Initial distillate value
u_{d_w}	uncertainty in productivity
α_w	Absorptivity of water
τ_w	Water transmissivity
α_b	absorber basin absorptivity
τ_g	Transmissivity of glass
α_g	Absorptivity of glass
m_w	Mass of water (kg)
m_b	absorber basin mass (kg)
m_g	glass mass(kg)
C_{pw}	Specific heat capacity of water (KJ/Kg-K)
C_{pb}	Specific heat capacity of absorber basin (KJ/Kg-K)
C_{pg}	Specific heat capacity - glass (KJ/Kg-K)
C_{pv}	Specific heat capacity - vapour mixture (KJ/Kg-K)
K_v	Thermal conductivity of vapour mixture (W/m-K)
d	space between the absorber water and inner glass (m)
g	Gravity (m/s ²)
β	Volume expansion coefficient (1/K)
dt	the difference in temperature between the absorber water and inner glass
ρ	Density (kg/m ³)
μ	Dynamic viscosity (N-s/m ²)
A_w	Area of water (m ²)
A_b	Area of absorber basin (m ²)
A_g	Area of glass (m ²)

h_c	coefficient of convective heat transfer - water (W/m ² K)
$h_{t,i}$	Total inner - coefficient of convective heat transfer (W/m ² K)
$h_{r,i}$	Inner - coefficient radiative heat transfer (W/m ² K)
$h_{e,i}$	inner - coefficient of evaporative heat transfer (W/m ² K)
$h_{t,o}$	Total outer - coefficient of convective heat transfer (W/m ² K)
$h_{c,i}$	Inner – coefficient of convective heat transfer (W/m ² K)
$h_{c,o}$	Outer - coefficient of convective heat transfer (W/m ² K)
$h_{r,o}$	Outer – coefficient of radiative heat transfer (W/m ² K)
U_b	Overall - basin heat transfer coefficient (W/m ² K)
T_w	Water temperature (°C)
T_g	Glass temperature (°C)
T_b	Absorber basin temperature (°C)
T_a	atmospheric temperature (°C)
T_s	Sky temperature (°C)
P_w	Partial pressure of water (N/m ²)
P_g	Partial pressure of glass (N/m ²)
ε_{eff}	Effective emissivity
ε_g	Emissivity of glass
ε_w	Emissivity of glass
σ	Stefan-Boltzmann constant (5.67×10^{-8} W/m ² K ⁻⁴)
$Q_{e,i}$	Inner Heat transfer (W)
L_h	Latent heat of vaporization of water (KJ/Kg)
P_h	Hourly productivity (kg)
P_d	Daily productivity (kg)
η_{ins}	Instantaneous thermal efficiency
$\eta_{passive}$	Cumulative still efficiency
I	Incident global solar radiation (W/m ²)
A	Area of the absorber basin (m ²)

Nu	Nusselt number
Gr	Grashoff number
Pr	Prandtl number
CSS	Conventional Solar Still
PCMAAF-SS	agar fibre and mPCM in the solar still
mL/m^2	Millilitre per day
cm	Centimetre
m	Metre
mm	Millimetre
m^2	Square metre
W/m^2	Watt per square metre
W	Watt
$^{\circ}\text{C}$	Degree Celsius
mL	Millilitre
KJ/Kg-K	kilojoule per kilogram Kelvin
W/m-K	Watt per metre Kelvin

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41 1. Introduction:

42 The most vital and primary nutrient for the survival of all living species on the earth is water. The earth's surface
43 is covered by 71 percent water, with freshwater accounting for only around 3% of the total. The remaining 97 %
44 of water is held by the ocean. The freshwater resources are rapidly depleting as a result of rapid population
45 expansion and industry exploitations. The depletion of freshwater resources leads to water scarcity and droughts.
46 The ocean water contains a high percentage of salt which cannot be consumed directly. The conversion of seawater
47 to safe drinking water has been the most effective way to overcome water scarcity. The desalination process
48 converts salt water into potable water. The desalination process is driven by conventional sources of energy.
49 Another serious concern that must be addressed is the carbon impact due to conventional energy (Mathioulakis et
50 al. 2007; Qiblawey and Banat 2008; Sharon and Reddy 2015; Patel et al. 2019; Ahmed et al. 2021). The best
51 possible solution is a renewable energy-driven desalination technology which can be accomplished with the help
52 of solar stills. The stills can be easily made by utilising locally accessible materials in any region. The construction
53 is simple, easy to handle and also cost-effective. The main downside of solar still is its lesser yield. Scientists

across the world are using different approaches to increase productivity (Thirugnanasambandam et al. 2010; Jani and Modi 2018; Bhargva and Yadav 2021; Ho et al. 2021; Singh et al. 2021). The various approaches for the enhancement of solar still productivity have been discussed elaborately in the literature review section.

2. Literature Review:

Productivity Enhancement of Solar still based on geometry and extended surfaces

The absorption of more global radiation in the still can be achieved by more surface area in the design (Kabeel et al. 2019)(Shinde et al. 2020). Sharshir et al. (Sharshir et al. 2020a) experimentally analysed the pyramid still with wick material and nanofluid, it was found that the pyramid solar still with wick material and copper oxide nanofluid has the higher productivity of about 72.95 % whereas for inclusion of wick in the pyramid still has 45 % increase in productivity relative to the conventional pyramid still. Dubey et al. (Dubey et al. 2021) analysed the environment, energy, exergy and economic for the double slope solar still connected with evacuated tubes. It was found that the high productivity of freshwater with emission reduction and less cost can be assessed using the integrated system. Hassan et al. (Hassan et al. 2019) investigated the influence of saline water in the solar still which was combined with a parabolic trough collector system. The study reveals that the sand and wire mesh medium increased the productivity by 13.7 % and 3.1 % compared to pure saline water. Mostafavi et al. (Mostafavi et al. 2020) developed a semi-analytical model for longitudinal and transverse fins into the Phase Change Materials for the solar thermal application system by using the perturbation method. The results showed that the extended surfaces in the solar thermal system increased productivity. Moungar et al. (Moungar et al. 2017) investigated the effects of fins which was immersed in the solar still. It was revealed that distance between fins has no significant improvement whereas the height of fins played a major role in productivity. The productivity was increased when the fin heights increased from 2 - 5 cm whereas the productivity was decreased when height changed from 6 to 8 cm. Suraparaju and Natarajan (Suraparaju and Natarajan 2021a) experimentally investigated the absorber basin with novel bottom finned absorber basin to improve the transfer of heat from absorber to the phase change materials under the basin. The experiment was carried out with three setups, one with a hollow finned absorber, and another with a solid fin absorber basin and conventional solar still. The experiment revealed that still with hollow finned absorber basin has higher productivity of 4085 mL/m²/day. The yield of solar still with solid fin absorber and conventional solar still was 3485 mL/m²/day and 2885 mL/m²/day. The hollow fin absorber basin has more solar still has more productivity because of the availability of space inside the hollow fins which helps to conduct more heat from the absorber to the latent heat storage system. Kabeel et al. (Kabeel et al. 2020) investigated the pyramid still with hollow fins and solid fins implanted into the

latent thermal storage material, the result showed that hollow fins pyramid solar still has increased in yield of 5.75 L/ m²/day whereas for solid fins it was 4.02 L/ m²/day. Modi and Jani (Modi and Jani 2021) assessed the double slope solar still without and with hollow fins analytically and experimentally. The theoretical and experimental results were compared and found that absorption of solar radiation was increased by 23.78 % with the inclusion of hollow fins, the productivity was increased by 51.74 %.

Productivity Enhancement by incorporation of Wick Materials

The wick material act as the porous medium in the absorber basin. The wick material increases more wet surface area, resulting in more evaporation (Fale et al. 2021) (Shubhajyothi et al. 2020). Sharshir et al. (Sharshir et al. 2020c) investigated the still with a novel wick-metal chip pad. The results showed that the copper metal chips in the pad enhanced the productivity by 54.2 % whereas in the aluminium chips filled pad the increase in productivity was 34.23 %. Modi and Modi (Modi and Modi 2020) experimentally analysed the wick pile of jute cloth in the single slope solar still with a double basin. The results revealed that the inclusion of wick material increased the productivity by 21.12 %, 23.71 % on the experiment days. Sharshir et al. (Sharshir et al. 2020b) studied the still with nanoparticles and linen wicks. The still with linen wick materials and nanoparticles of black colour increased the productivity by 80.57 % and energy efficiency was increased by 110.5 %. Saravanan and Murugan (Saravanan and Murugan 2020) investigated the inclusion of various wick materials such as terry cotton, jute cloth, polyester and woollen fabrics in the square pyramid solar still. The results stated that the inclusion of woollen fabrics has better productivity which was 40.3 % more than conventional solar still, 33.1 %, 20.9 % and 9.4 % higher than that of polyester cloth, terry cotton and jute cloth respectively. Baskaran et al. (Baskaran et al. 2021) investigated the solar still with cotton gauze as wick material and it was found that the productivity was increased by 46.49 %. Younes et al. (Younes et al. 2021) experimentally investigated the solar still with corrugated wick and half barrel wick solar still. The results revealed that the increase in productivity for solar still with half barrel wick and the corrugated wick was 52 % and 43 % when compared with CSS.

Enhancement in productivity by Coating/Inclusion of Micro/Nano Particles in solar still

The temperature of the water can be increased by the inclusion of micro/nanoparticles in the absorber basin. The micro/nanoparticles absorb more heat from global solar radiation. The rise in water temperature leads to more evaporation resulting in enhancement of productivity. The graphite nanofluid and copper oxide nanofluid increased the productivity by 41.18 % and 32.32 % relative to CSS (Sharshir et al. 2018). Asadpourian and Ameri (Asadpourian and Ameri 2021) analysed the CuO-GO nanocomposite in the solar still. The result showed that the 0.3, 0.2 and 0.1 mass% of nanocomposite increased the freshwater productivity by 44.7 %, 75 % and 91.7 %

respectively. Kandeal et al. (Kandeal et al. 2021) investigated the combination of inclusion of Cu_2O nanoparticles and nano-enhanced PCM in the solar still. The result indicated that the combination of nanoparticles and nanophase change materials enhanced the productivity by 113% when compared to conventional solar still. The inclusion of naturally available nano/microparticles enhanced the evaporation rate. Baskaran and Saravanane (Baskaran and Saravanane 2021) experimentally studied the montmorillonite nanoparticles for desalination. The yield obtained was about 5.33 to 6.45 $\text{kg/m}^2/\text{day}$ during 14 testing days. Sampathkumar and Natarajan (Sampathkumar and Natarajan 2021a) experimentally investigated the inclusion of *Borassus Flabellifer* micro-sized particles in the absorber basin. It was found that productivity was increased by 35% on day 1 and 33% on day 2.

Productivity Enhancement of Solar Still by Inclusion of Thermal Storage System

The inclusion of thermal storage systems such as Latent Heat and Sensible Heat Storage extended the operating time of solar still. The thermal storage systems absorb heat during diurnal and release it during nocturnal.

Sensible Thermal Storage

The sensible thermal storage materials absorb heat during the daytime and release it after the sunset without any change in its phase. Mohamed et al. (Mohamed et al. 2019) studied the performance of solar still by the inclusion of basalt stone as a sensible energy medium. The productivity was increased by 33.37 %, 27.86 % and 19.81 % when the size of the stone was 2, 1.5 and 1 cm, respectively. Gholizadeh and Farzi (Gholizadeh and Farzi 2020) analysed the still with sand as thermal storage, the results showed that the productivity was increased by 21.16 % relative to still without any thermal storage. Attia et al. (Attia et al. 2021) experimentally investigated the El Oued sandbags of 25 numbers, the results showed a 34.83 % increase in productivity. Arunkumar et al. (Arunkumar et al. 2020) experimentally investigated the solar still with different sensible storage materials such as spherical clay balls, Polyvinyl Alcohol sponges, pebbles and absorber plates coated with copper oxide nanoparticles. From the experiments, it was found that the productivity of solar still with absorber plates coated with copper oxide nanoparticles, spherical clay balls, pebbles and Polyvinyl Alcohol sponges were 2.9, 2.6, 2.8 and 1.9 $\text{L/m}^2.\text{day}$ respectively. Panchal et al. (Panchal et al. 2020) analysed the still with evacuated tubes and calcium stones. It was found that productivity was enhanced by 104.68 % for the solar still contains evacuated tube with calcium stone whereas for solar still with the evacuated tube was 113.52 %. Dubey and Mishra (Dubey and Mishra 2020) analysed the double-slope still with ring magnets made up of ferrite and Galvanized Iron sheets. It was found that the increment of yield was 31.13 % and the exergy efficiency was increased by 57.58 %. Rajmanickam et al. (Rajamanickam et al. 2018) analysed the solar still with charcoal as energy storage

material and the productivity was enhanced by 30.57 % relative to CSS. Thakur et al. (Thakur et al. 2021) analysed the solar still integrated with a line focusing collector for the preheat of feed water and included activated carbon pellets for the energy storage. The results showed that productivity was increased by 85.2 % in comparison with CSS. The preheating of feed water and inclusion of energy storage medium enhanced the productivity.

Latent Thermal Storage

The latent thermal storage materials absorb heat during sunshine hours and change their phase from solid to liquid. The absorbed heat energy was released during non-sunshine hours and returned to solid-state. The impregnation of micro/nanoparticles enhanced the thermal properties of novel PCM (Tariq et al. 2020)(Peng et al. 2021). Nian et al. (Nian et al. 2021) studied the solar still throughout a year with an absence of phase change energy materials, the results indicated that the incorporation of phase change materials in the solar still increased the productivity by 71.2 % in comparison with conventional solar still without any energy storage medium. Shoeibi et al. (Shoeibi et al. 2021) studied the influence of the absorber coated with nano-particles and nano-enhanced PCM. The CuO and Al₂O₃ with the wt% of 0.1 and 0.3 respectively were mixed with phase change material and the black paint with copper oxide nanoparticles coated for absorber and the experiment was carried out. The results showed that productivity was increased by 55.8 and 49.5 % for copper oxide and aluminium oxide nano-enhanced phase change material when compared with conventional still. Additionally, the nano-coated black paint increased the water production rate by 5.7 %. Russ et al. (Iniyan and Suganthi 2017) investigated the solar still with 0.3 wt% copper oxide phase change material and found that the productivity was enhanced by 35%. Rufuss et al. (Dsilva Winfred Rufuss et al. 2018) studied the nano enhanced phase change materials with three nanoparticles such as titanium oxide, copper oxide and graphene oxide. The different nano enhance phase change materials were utilised for the solar still as thermal storage medium. The results revealed that the increased in productivity was 26% and 35 % for nano enhanced TiO₂ and CuO phase change materials respectively. It was also recommended that solar still with CuO nano enhanced PCM of 0.3 weight% for better yield. Safaei et al. (Safaei et al. 2019) analysed the Graphene Oxide as the nanoparticles mixed with phase change material in the weight % of 0.2, 0.4 and 0.6. The increase in productivity of 25 % was obtained for 0.6 wt% nano enhanced phase change material.

The novelty of the work

From the summary of the literature survey, it was clear that the productivity of solar still can be increased by various approaches such as improvement of evaporation rate and enhancing productivity by the inclusion of

thermal energy storage systems. The majority of the researchers examined the impact of nano/microparticles coated absorber basins. Some researchers investigated the inclusion of synthesised nanoparticles and naturally available microparticles in the absorber of solar still. Many researchers experimentally analysed the inclusion of thermal energy materials in the solar still to increase the operating time during non-sunshine hours. However, to the best of the author's knowledge, there was no specific work that focuses on the investigation of the combined effect of inclusion of Borassus Flabellifer Micro-Sized Particles in the absorber basin and micro Phase Change Material under the absorber basin for the enhancement of productivity.

The main objectives of this work are

1. To estimate the optimum weight of micro-sized palm powder in the absorber for maximum productivity.
2. To determine the optimised weight% of palm powder impregnated with phase change material – paraffin wax for the better thermal energy storage system.
3. The experimentation of solar still with the combination of better weight% mPCM under the absorber basin and optimum weight of palm flower powder- micro-size in the absorber basin.
4. The evaluation of thermal, economic and environmental analysis of PCMPFP-SS and CSS.

The experimental investigation with different weights of micro-sized particles such as 10 g, 30 g, 45g, 50 g, 55 g, 70 g, 100 g, 120 g, and 150 g in the absorber basin was performed. The experimental investigation has been carried out to determine the better wt% of micro-sized particles in the paraffin wax for enhanced thermal properties. The experimental analysis with the optimum weight of micro-sized particles in the absorber basin and better weight% of mPCM bed under the absorber basin was carried out during September 2021 at Science Block, National Institute of Technology Puducherry.

3. Materials and Methods

This section involves the fabrication of solar still, selection of material, preparation of mPCM, and methodology.

The experimental work was performed along with error analysis was included.

3.1 Materials and Setup of solar still

Four similar solar stills were developed at the terrace of Science block, National Institute of Technology, Puducherry (10.98 °N, 79.84 °E) and the experimental setup is given in figure 1. The solar stills were fabricated with plywood because of the better durability and stability of plywood. The interior area of solar stills was covered with a 2 mm thick aluminium sheet to reduce the interface of moisture with plywood. The aluminium sheet was coated with black colour to absorb more insolation. The thermocol of 3 cm thick was used to cover the outer sides of the solar still to prevent loss of heat to the atmosphere. The dimensions of each copper basin were 100 × 60 ×

5 cm (length $\times$ width $\times$ height). The thickness of the copper absorber basin was 1 mm. The copper absorber basin was coated with selective coating ThurmaloX because of its high absorptivity property. The saline water depth in the absorber basin was 2 cm and it was maintained throughout the experiment day. The top of solar still was enclosed with 4 mm thick transparent glass. The CPVC pipe was attached at the end of the solar still facing south to collect the freshwater from the bottom of the transparent glass cover. The measuring cylinder was positioned near the connecting pipe to collect the freshwater from the connected pipe.

Fig 1. Experimental setup of solar stills

3.2 Materials

The naturally available and low-cost materials were chosen for the productivity enhancement in the solar still. The material selected for the experimental work was male palm flower powder. The *Borassus Flabellifer* tree is native to India and Southeast Asia. The fruits from the tree have medicinal value, the other portions such as leaf, trunk, crown and roots were used for a variety of purposes. The flower from the male palm tree has good thermal properties. The palm tree was found abundant near the testing location, National Institute of Technology, Puducherry (NITPy). The palm tree flower was collected from the nearby testing range and blended into uniform micro-sized particles (Sampathkumar and Natarajan 2021a). The phase change material chosen for the preparation and experimentation of mPCM was paraffin wax. The paraffin wax was chosen because it has fast charging and high latent heat of absorption capacity. Furthermore, the paraffin wax is easily obtainable, safe to

use and less toxic (Suraparaju et al. 2021b). The required paraffin wax for preparation of mPCM samples and experimentation was procured from the local marketplace.

3.3 Preparation of mPCM

The thermal conductivity of Phase Change material can be enhanced by the incorporation of micro-sized particles. The micro enhanced Phase Change Material reduced the charging time. The micro-sized particles fill the space between molecules of PCM and enhance the transfer of heat between the molecules. There is no substantial increment in thermal properties when more weight% of micro-sized particles are added to the paraffin wax. The optimum weight% of micro-sized particles enhances the thermal properties. In this regard, the samples were prepared with different weight% of micro-sized palm powder such as 5, 10, 15 and 20 wt%. The paraffin wax was weighed using SHIMADZU CORPORATION BL – 220 H Type electronic balance machine. The paraffin wax was heated above its melting temperature using a hot plate of 12" diameter, 1500 Watts and 230 Volts. The micro-sized palm flower powder was mixed with liquid paraffin using a probe sonicator of model SM750PS. The samples with different weight% of micro-sized palm flower powder such as 5, 10, 15 and 20 wt% were prepared. Each sample was sonicated with 1.5 kHz for half an hour. The samples were allowed to cool until they attained stable equilibrium. The thermal conductivity of each sample was measured using TEMPOS thermal properties analyser TR-3 single needle of 2.4 mm diameter and 100 mm length. The process of preparation of sample with different weight% such as 5, 10, 15 and 20 wt% and the measurement of thermal conductivity of the sample is presented in figure 2. The results of thermal conductivity with different weight% of palm flower powder is shown in figure 3.

It was observed that the thermal conductivity of mPCM with 5, 10, 15 and 20 wt% of micro-sized palm flower powder were 0.25, 0.30, 0.31 and 0.33 W/m-K respectively. From experiments, it was found that the thermal conductivity of mPCM with 25 wt% of micro-sized palm flower powder was 0.33 W/m-K. The micro-sized palm flower powder sediment at 25 wt% of micro-sized palm flower powder in paraffin wax and there was no improvement in the thermal conductivity. The micro-sized particles occupied the space between molecules of paraffin wax and improved the heat transfer between the molecules. From the results, it was clear that the maximum thermal conductivity was attained at 20 wt% of palm flower powder in the paraffin wax which was 57.14 % higher than novel paraffin wax.

(a)

(b)

(c)

(d)

Fig. 2 (a) Hot Plate to melt PCM (b) Sonication process (c) Samples with different weight% (d) TEMPOS thermal properties analyser

Fig. 3. Effect of thermal conductivity for different weight% of palm powder

3.4 Experimental and Error Investigation

The k type thermocouples were placed at the glass, water, absorber basin and PCM bed. The thermocouples were coupled to the Agilent 3492A Data acquisition system for recording the temperatures. The global radiation was measured using Hukseflux Pyranometer. The temperatures at various locations on solar stills, global solar radiation and productivity were recorded for every half an hour from 08:00 A.M to 08:00 P.M (IST) during experiment days. Figure 4 depicts the methodology for the overall experimentation process.

Fig 4. Methodology for the experimentation of PCMPFP-SS

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The experiments were conducted to determine the optimal weight palm flower powder of micro-size in the absorber for better productivity. The effect of various weights of palm flower powder of micro-size in the absorber basin was also investigated. In this regard, the different weights of palm flower powder of micro-size such as 10 g, 30 g, 50 g, 70 g, 100 g, 120 g, and 150 g were experimentally investigated. The increase in productivity of different weights of palm flower powder of micro-size in the absorber basin is shown in figure 5.

Fig. 5 Increase in productivity with different weight%

From figure 5. it can be seen that the solar still with 50 g of palm flower powder of micro-size in the absorber basin has the better productivity of 37.25 %, whereas, for 10 g, 30 g, 70 g, 100 g, 120 g, and 150 g the increase in productivity was 11.85 %, 24.78 %, %, 34.35 %, 33.05 %, 10.25 % and -20.22 % respectively. It was inferred from the experimental results, that the more weight of palm flower powder of micro-size in the absorber basin completely hindered the evaporation and the productivity was very much lower than conventional solar still. On the other hand, the contribution of the lesser weight of palm flower powder of micro-size in the absorber basin for the enhancement of productivity was very minimal. The optimum weight of palm flower powder of micro-size in the absorber basin for better productivity was 50 g. The experiments were carried out with 45 g and 55 g of palm flower powder of micro-size in the absorber basin, the observed productivity was 36.1 % and 36.8 % respectively.

3.4.1 Preparation of mPCM bed and Experimentation:

The paraffin wax of 10 kg was filled in the solar still and allowed to change its phase from solid to liquid by absorbing solar radiation. The micro-sized palm flower powder of 20 wt% was mixed with liquid paraffin wax and allowed to solidify. It was ensured that the micro-sized particles were well mixed with liquid paraffin wax in the solar still. It was allowed to cool and attain its equilibrium state. The preparation of the mPCM bed is shown in figure 6.

The solar stills developed for the experimentation were solar still with the optimum weight of palm flower powder of 50 g in the absorber basin, 20 wt% of mPCM bed under the absorber basin and the Conventional Solar

283 Still. On experiment days, the absorber basin was placed over the mPCM bed and saline water was filled with 2
284 cm depth. The 50 g weight palm flower powder of micro-size was spread over the surface of the water in the
285 absorber. The top of solar still was enclosed with 4 mm thick transparent glass and ensured no heat leakage to
286 the ambient. The experimental setup of the combined effect of inclusion of micro-sized particles in the absorber
287 basin, mPCM and CSS is shown in figure 7.

288

(a)

(b)

Fig 6 (a) paraffin wax in liquid state (b) mPCM bed

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Fig.7 Experimental setup of PCMPFP-SS and CSS

The errors occur due to measuring instruments and during experimentation. The uncertainty of an experiment is due to random and systematic error. The uncertainty of each equipment associated with the experiment can be calculated using equation (1) (Suraparaju et al. 2021a)(Natarajan et al. 2021), the uncertainty in the productivity of each hour can be evaluated using equation 2 (Suraparaju and Natarajan 2021a)(Sampathkumar and Natarajan 2021b). The range, accuracy and uncertainty of each instrument was calculated using equation 1 and it is presented in table 1.

$$U = \frac{A}{\sqrt{3}} \quad (1)$$

Table 1. Uncertainty of instruments

S. No	Instrument details	Accuracy (A)	Range	Uncertainty (U)
1	Thermal Properties analyser	$\pm 10\%$ W/mK	0.1-4.0 W/mK	0.058 W/mK
2	K type thermocouple	± 0.1 °C	-270 to 1,260 °C	0.058 °C
3	Pyranometer	± 10 W/m ²	0 to 1600 W/m ²	5.774 W/m ²

4	Cylinder	5 ml	0 to 1000 ml	2.89 ml
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$$u_{d_w} = \left[\left(\frac{d_i - d_f}{\delta y_1} u_y \right)^2 \right]^{\frac{1}{2}} \quad (2)$$

$d_i - d_f$ is the difference between initial and final distillate at any time and u_y is the uncertainty in productivity.

4. Thermal, Economic and Environmental Analysis

For the thermal evaluation, the succeeding assumptions are made and are listed below (Sharshir et al. 2017)

(Dhivagar et al. 2021)(Elango et al. 2015)

- The solar still is in quasi-static condition
- There is no potential, kinetic impact on the solar still
- The inclination in transparent glass is constant
- The water depth is constant in the solar still
- There are no specific heat capacity for insulation and glass cover
- The thermophysical properties of water and glass cover are constant

In the thermal analysis the energy balance between solar still and global radiation is calculated by the energy balance equations and also the overall efficiency of the solar still can be calculated from the utilisation of global solar radiation with considering the heat transfer loss inside and outside solar still (Sharshir et al. 2017) (Dhivagar et al. 2021)(Elango et al. 2015). The equations of energy balance for water, absorber basin and glass for the solar still is presented from equations (3) to (7). The convection mode of heat transfer occurs between water and inner glass, the heat transfer coefficient in terms of Nusselt number is given in equation (8), and the Nusselt number is the function of two dimensionless numbers namely Grashof number and Prandtl number which are presented in equation (10) and (11), respectively. The total heat transfer coefficient inside the solar still and the total coefficient of heat transfer between glass cover and ambient is presented from equation (12) to (21) and equation (22) to (26) respectively. The hourly productivity and daily productivity of solar still can be calculated from equations (27) and (28). The instantaneous thermal efficiency and overall cumulative efficiency of the solar still is given in equations (29) and (30) respectively.

Energy balance equations for saline water in the absorber

$$\alpha_w \tau_w I A_w + h_c (T_b - T_w) = m_w C_{pw} \frac{dT_w}{dt} + h_{t,i} (T_w - T_g) \quad (3)$$

$$h_{t,i} = h_{c,i} + h_{r,i} + h_{e,i} \quad (4)$$

327 Energy balance equation for absorber basin

$$\alpha_b \tau_w \tau_g I A_b = m_b C_{pb} \frac{dT_b}{dt} + h_c (T_b - T_w) + U_b (T_b - T_a) \quad (5)$$

328

329 Energy balance equation for glass cover

$$\alpha_g I A_g + h_t (T_w - T_g) = m_g C_{pg} \frac{dT_g}{dt} + h_{t,o} (T_g - T_s) \quad (6)$$

$$h_{t,o} = h_{c,o} + h_{r,o} \quad (7)$$

330

331 The convective heat transfer in terms of Nusselt number

$$Nu = \frac{h_{c,i} \times d}{K_v} \quad (8)$$

$$Nu = f(Gr, Pr) \quad (9)$$

332

333 Where

$$Gr = \frac{g \beta d t d^3 \rho^2}{\mu^2} \quad (10)$$

$$Pr = \frac{\mu C_{pv}}{K_v} \quad (11)$$

334

335 The convection mode of heat transfer between saline water and the glass is

$$Q_{c,i} = h_{c,i} (T_w - T_g) \quad (12)$$

$$h_{c,i} = 0.884 \times \left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{\frac{1}{3}} \quad (13)$$

$$P_w = e^{\left(25.317 - \frac{5144}{T_w + 273}\right)} \quad (14)$$

$$P_g = e^{\left(25.317 - \frac{5144}{T_g + 273}\right)} \quad (15)$$

336

337 The convection mode of heat transfer between saline water and the glass

$$Q_{r,i} = h_{r,i} (T_w - T_g) \quad (16)$$

$$h_{r,i} = \varepsilon_{eff} \times \sigma \left[(T_w + 273)^2 + (T_g + 273)^2 + (T_w + T_g + 546) \right] \quad (17)$$

$$\varepsilon_{eff} = \left(\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_w} - 1 \right)^{-1} \quad (18)$$

338

339 The evaporation heat transfer between saline water and the glass

$$Q_{e,i} = h_{e,i} (T_w - T_g) \quad (19)$$

$$h_{e,i} = 13.273 \times 10^{-3} \times h_{c,i} \times \left[\frac{(P_w - P_g)}{(T_w - T_g)} \right] \quad (20)$$

340

341 The coefficient of overall heat transfer between water and glass is given by

$$h_{t,i} = h_{c,i} + h_{r,i} + h_{e,i} \quad (21)$$

342

343 The convection mode of heat transfer from glass to ambient

$$Q_{c,o} = h_{c,o} (T_g - T_a) \quad (22)$$

$$h_{c,o} = 2.8 + (3.0 \times v) \quad (23)$$

344

345 The radiation heat transfer from glass cover to ambient

$$Q_{r,o} = h_r (T_g - T_a) \quad (24)$$

$$h_{r,o} = \varepsilon_g \times \sigma \left[\frac{(T_g + 273)^4 - (T_s + 273)^4}{(T_g - T_a)} \right] \quad (25)$$

$$T_s = T_a - 6 \quad (26)$$

346

347 The hourly, daily productivity of solar still and instantaneous thermal efficiency is

$$P_h = \frac{Q_{e,i}}{L_h} \times 3600 \quad (27)$$

$$P_d = \sum_{i=1}^{24} P_h \quad (28)$$

$$\eta_{ins} = \frac{Q_{e,i}}{I} \quad (29)$$

348

349 The cumulative efficiency of the solar still is

$$\eta_{passive} = \frac{\sum P_h \times L_h}{\sum I \times A \times 3600} \quad (30)$$

350

351 Where $\sum P_h$ is the total yield on the day (kg), L_h is the latent heat of vaporisation of water (J/Kg), A is absorber
352 basin (m²) and $\sum I$ is the cumulative global radiation (W/m²) on the experiment days.

353 The influence of modified solar still can be evaluated by comparing the increase in productivity with the
354 conventional solar still. The altered solar still contains fibres and latent thermal storage materials. It is important
355 to consider the economic view for modified solar still. The main objective of the economic analysis is to evaluate
356 the Cost per Litre (CPL) and payback period of solar stills. The following assumptions are made for the analysis

- 357 1. The rate of interest, r is 15 %.
- 358 2. The salvage value is determined as 20 per cent of the fixed cost.
- 359 3. The lifespan of solar stills is 10 years

4. The operation of solar still in a year is 280 days

The CPL and payback period for the PCMPFP-SS and CSS can be calculated using the following equations (Suraparaju and Natarajan 2021a) (Suraparaju and Natarajan 2021b)

$$\text{First Annual Cost} = \text{Capital Recovery Factor} \times \text{Initial Investment} \quad (31)$$

$$\text{Capital Recovery Cost} = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (32)$$

$$\text{Annual Sinkage Factor} = \text{Sinking Fund Factor} \times \text{Salvage Value} \quad (33)$$

$$\text{Sinking Fund Factor} = \frac{r}{(1+r)^n - 1} \quad (34)$$

$$\text{Salvage Value} = 0.2 \times \text{Initial Investment} \quad (35)$$

$$\text{Annual Maintenance Cost} = 0.15 \times \text{First Annual Cost} \quad (36)$$

$$\text{Annual Cost} = \text{First Annual Cost} + \text{Annual Maintenance Cost} \quad (37)$$

$$- \text{Annual Sinkage Factor}$$

$$\text{Cost Per Litre} = \frac{\text{Annual Cost}}{\text{Yield for 280 days}} \quad (38)$$

$$\text{Payback period} = \frac{\text{Net investment}}{\text{Total earned}} \quad (39)$$

$$\text{Total earned} = \text{waterprice in market for a litre} \times \text{Productivity per square metre} \quad (40)$$

The carbon footprint from the solar stills was utilised for the evaluation of environmental analysis. The intensity of CO₂ during the generation of electricity from coal is 0.98 kg CO₂ per kWh. The average distribution and transmission losses in Indian conditions are considered for analysis as 20 % and 40 % respectively, then the figure 0.98 can be taken as 1.58. The total embodied energy E_{in} of PCMPFP-SS and CSS, annual energy output E_{out} , CO₂ emission, CO₂ mitigation, net carbon dioxide mitigation (NCEM) and carbon credit gained can be calculated from the following equations (Suraparaju and Natarajan 2021a) (Suraparaju and Natarajan 2021b).

$$\text{Annual CO}_2 \text{ emission (kg)} = \frac{E_{in} \times 1.58}{n} \quad (41)$$

$$\text{CO}_2 \text{ emission (kg)} = E_{in} \times 1.58 \quad (42)$$

$$E_{out} = \frac{M \times L_h}{3600} \quad (43)$$

$$\text{CO}_2 \text{ mitigation (kg)} = E_{out} \times n \times 1.58 \quad (44)$$

$$\text{NCEM (in tons)} = \frac{[(E_{out} \times n) - E_{in}] \times 1.58}{1000} \quad (45)$$

$$\text{Carbon Credit Gained (\$)} = \text{NCEM} \times \text{Cost of CO}_2 \text{ traded per ton} \quad (46)$$

5. Results and Discussion

5.1 Ambient temperature, global radiation on experiment days

The insolation and temperature of the atmosphere on the testing days are shown in figure 8. The global radiation and ambient temperature readings were recorded at an interval of every half an hour from 8:00 A.M (IST) to 8:00 P.M (IST) on the experimentation days. The maximum solar radiation recorded on day 1 and day 2 were 974.95 W/m². The cumulative global radiation on day 1 was slightly higher than on day 2. The cumulative global radiation on day 1 and day 2 were 14441.44 W/m² and 14150.30 W/m².

Figure 8. Variation of ambient temperature and solar radiation

The ambient temperature rises steadily reaches the maximum at noon and starts falling afternoon. The ambient temperature lies between 25.4 °C and 31.4 °C on day 1 whereas for day 2 it was between 25.1 °C and 31.1 °C. The range of atmospheric temperature and global solar radiation was almost similar on both days.

5.2 Effect of micro-sized particles in the absorber basin & micro PCM on the temperatures of solar still

The temperatures at various locations such as glass, water, absorber for PCMPFP-SS and CSS on day 1 and the temperatures at the glass, water, absorber and mPCM bed for PCMPFP-SS are shown in figure 9. The maximum glass, water and absorber temperatures for CSS on day 1 were 54.4 °C, 68.9 °C and 70.9 °C. The maximum glass, water and absorber and mPCM bed temperature attained in PCMPFP-SS on day 1 were 54.1 °C, 69.9 °C and

387 71.1 and 59.1 °C. The water and absorber temperature was less during the morning when compared to glass
 388 temperature.

Figure 9. Variability in solar still temperatures - day 1

389
 390 The temperature at the glass, water, absorber and mPCM for PCMPFP-SS and CSS on day 2 is shown in figure
 391 10. The maximum glass, water and absorber temperatures for CSS on day 2 were 57.4 °C, 68.1 °C and 69.5 °C.
 392 The maximum glass, water and absorber and mPCM bed temperature attained in PCMPFP-SS on day 2 were
 393 57.5 °C, 68.9 °C and 70.4 °C and 58.5 °C. The water and absorber temperature was less during the morning when
 394 compared to glass temperature. The peak temperature at the glass, water, absorber and mPCM was attained from
 395 1:00 P.M (IST) to 1:30 P.M (IST) on both days.

396

Figure 10. Variability in solar still temperatures - day 2

The insolation on the experiment days increased the water and absorber temperature. The water temperature of PCMPFP-SS was higher than CSS due to the inclusion of micro-sized particles in the absorber basin. The micro-sized particles in the absorber basin increased the surface area and water temperature by the absorption of heat from global radiation. The higher water temperature in PCMPFP-SS leads to more evaporation rate. It was observed from the results that the temperature of glass in PCMPFP-SS was slightly lesser than CSS. This is due to the transfer of heat to mPCM under the absorber. It was noticed that the temperature of the absorber in PCMPFP-SS was higher than CSS was extended during non-shine hours. The heat absorbed by mPCM was released to the absorber and returned to the solid by releasing the stored energy. The temperature difference between water and glass for evaporation was extended even after the non-shine hours. The productivity in conventional solar still was ended from 5:00 to 5:30 P.M (IST) on both days, whereas the productivity in PCMPFP-SS was extended up to 8:00 P.M (IST).

5.3 Productivity

The instantaneous productivity for CSS and PCMPFP-SS on day 1 & 2 are presented in figure 11. The cumulative productivity for CSS and PCMPFP-SS on day 1 and day 2 are presented in figure 12.

Figure 11. Solar stills instantaneous productivity on day 1 and day 2

413

Figure 12. Solar stills cumulative productivity on day 1 and day 2

414

From figure 11 it was clear that the maximum hourly productivity for PCMPFP-SS was 470 ml/m²-day on day 1 and 400 ml/m²-day on day 2. The maximum hourly productivity occurred at 01:30 P.M (IST) on day 1 and day 2. The maximum hourly productivity for CSS was 380 ml/m²-day on day 1 and 320 ml/m²-day on day 2. The yield of CSS and PCMPFP-SS upto 5:00 P.M (IST) were 3030 ml/m²-day and 4420 ml/m²-day respectively. The yield of CSS and PCMPFP-SS upto 5:00 P.M (IST) on day 2 were 2800 ml/m²-day and 3980 ml/m²-day respectively. The increase in productivity of PCMPFP-SS on day 1 and day 2 was due to the inclusion of palm flower powder in the absorber. The hourly productivity of PCMPFP-SS decreased gradually after 05:30 P.M (IST) and ended at 08:00 P.M (IST) whereas for CSS it was ended at 05:00 P.M (IST). The continuation of hourly productivity in PCMPFP-SS on day 1 and day 2 was due to the inclusion of the mPCM bed. From figure 12. it is clear that the aggregated productivity of PCMPFP-SS was higher than CSS. The yield for CSS attained steady after 5:00 P.M (IST) to 5:30 P.M (IST) on both days whereas for PCMPFP-SS the yield continued till 07:30 P.M (IST). The productivity of both PCMPFP-SS and CSS was higher on day 1 compared to day 2 because of more insolation on day 1. The total yield of CSS and PCMPFP-SS on days 1 and 2 are represented in figure 13.

Figure 13. Total yield comparison of solar still on day 1 and day 2

From the figure, it is clear that the yield of PCMPFP-SS was higher than CSS. The total yield for PCMPFP-SS was 4670 ml/m²-day on day 1 and 4250 ml/m²-day on day 2. The total yield for CSS was 3030 ml/m²-day on

day 1 and 2800 ml/m²-day on day 2. The increase in productivity of solar still with micro-sized particles in the absorber basin & micro Phase Change Material at bottom of the basin was 54.12 % on day 1 and 51.78 % on day 2 compared to conventional solar still. The increase in productivity was due to the combined effect of the inclusion of palm flower powder-micro size in the absorber and mPCM bed under the absorber.

5.4 Effect of micro-sized particles in the absorber basin & micro PCM on the productivity of solar still

The productivity was enhanced significantly due to the inclusion of palm flower powder micro-sized in the absorber basin. The palm flower powder of micro-sized in the absorber basin increased the more surface area for evaporation. The global radiation increased the water temperature of PCMPFP-SS than CSS. It was observed that the inclusion of palm flower- micro-sized powder increased the evaporation rate. The amount of palm flower powder in the absorber basin played a significant role in the increase of productivity. The more amount of palm powder in the absorber completely obstructed the evaporation. It was observed that due to the presence of more amount of palm flower powder in the absorber basin the insolation takes more time to raise the water temperature hence the evaporation was reduced drastically. On the other hand, there was no significant improvement in productivity with the minimal amount of palm powder in the absorber. Additionally, the inclusion of mPCM bed under the absorber basin extended the hourly productivity upto 8:00 P.M (IST). The heat was transferred to mPCM during sunshine hours and the state of phase change material was changed from solid to liquid. The stored heat was released to the absorber and returned to its original state. It was observed that the productivity of PCMPFP-SS after 5:00 P.M (IST) were 1640 ml/m²-day on day 1 and 1450 ml/m²-day on day 2. The inclusion of a thermal energy storage system increased the operating time of solar still resulting in extended hourly productivity relative to CSS. The overall yield results indicated that the inclusion of optimum weight of palm flower powder in the absorber enhanced the rate of evaporation and the inclusion of mPCM bed increased the operating time of solar still. The combined effect of the inclusion of palm flower powder micro-sized and mPCM enhanced the productivity of PCMAAF-SS relative to CSS.

5.5 Thermal Economic and Environmental Analysis

The efficiency of both the PCMPFP-SS and CSS were calculated for both the days of experimentation. The results showed that the efficiency for PCMPFP-SS was 42.59 % on day 1 and 39.57 % on day 2. The efficiency for CSS was 27.68 % and 26.07 % for day1, day 2 respectively. The increase in efficiency for PCMPFP-SS was 53.8 % on day 1 and 51.7 % on day 2. The increase in efficiency was due to the inclusion of micro-sized particles and thermal storage in the solar still. The thermal storage materials increased the operating hours of solar still, hence the productivity was increased. The Cost per Litre and payback period for PCMPFP-SS and CSS were

calculated using equations from (4) to (13). The value for each parameter is presented in table 2. The cost per litre and payback period for PCMPFP-SS and CSS is presented in figure 14. The individual components of embodied energies are presented in table 3. The results from the evaluation of environmental analysis are given in table 4.

Table 2. Economic Analysis of CSS and PCMPFP-SS

Parameters	CSS	PCMPFP-SS
<i>Initial Investment</i>	₹ 9000	₹ 11000
<i>Capital Recovery Cost</i>	0.198	0.198
<i>First Annual Cost</i>	1782	2178
<i>Sinking Fund Factor</i>	0.049	0.049
<i>Salvage Value</i>	1800	2200
<i>Annual Sinkage Factor</i>	88.2	107.8
<i>Annual Maintenance Cost</i>	270	330
<i>Annual Cost</i>	1981	2422
<i>Yield for 280 days</i>	816 L/ m ²	1248 L/ m ²
<i>Cost Per Litre</i>	₹ 2.4 = 0.032 USD	₹ 1.9 = 0.025 USD
<i>Payback period</i>	5.1 months	4.1 months

Figure 14. Comparison of CPL and Payback Period of both solar still

Table 3. Embodied energies of CSS and PCMPFP-SS

Components	Setup	Setup Inner layer	Basin	Cover	Insulation	Basin Coating	Storage Medium	Total embodied energy (E_{in})	
Materials	Plywood	Aluminium	Copper	Glass	Thermocol	Black paint	PCM	MJ	kWh
Weight (kg)	20	4	10	6	0.3	0.2	10	-	-
Specific Embodied Energy (MJ/kg)	18	330	90	15	117	90	26.2	-	-
Embodied energy (MJ) for CSS	360	1320	900	90	35.1	18	-	2723.1	756.4
Embodied energy (MJ) for PCMPFP-SS	360	1320	900	90	35.1	18	262	2985.1	829.1

Table 4. Environmental Analysis of CSS and PCMPFP-SS

Parameters	CSS	PCMPFP-SS
Embodied Energy E_{in} , (kWh)	756.4	829.1
Annual Energy Output, E_{out} , (kWh)	679.7	1040
Lifetime CO ₂ emission for (kg)	1195.11	1309.97
Lifetime CO ₂ mitigation (ton)	10.7	16.4
Lifetime net CO ₂ mitigation (ton)	9.54	15.12
Gain of Carbon Credit (\$)	133.56	211.68

474

475 The Cost per Litre for PCMPFP-SS and CSS were \$ 0.025 and \$ 0.032 respectively. The payback period for
476 PCMPFP-SS was reduced from 5.1 months to 4.1 months. The embodied energies of each component associated
477 with PCMAAF-SS and CSS are presented in Table 3. The results of different parameters from the environmental
478 investigation are shown in table 4. The solar stills lifespan was taken as 10 years. The total embodied energy
479 associated with CSS and PCMPFP-SS were 756.4 kWh and 829.1 kWh respectively. The net CO₂ mitigation for
480 the lifetime (in ton) of PCMAAF-SS was higher than CSS. From the economic point of view, the carbon credited
481 for 1 ton is equal to \$ 14, from the analysis it was shown that the gain of carbon credit from PCMPFP-SS and
482 CSS were \$ 211.68 and \$ 133.5 respectively.

483 **Conclusion:**

484 The purpose of this work was to experimentally investigate the productivity enhancement of single slope solar
485 still by the inclusion of naturally available Borassus Flabellifer micro-sized particles in the absorber basin and
486 micro Phase Change Material (mPCM) under the absorber basin. The experiments were carried out with different
487 weights of palm powder-micro sized in the absorber basin of solar still such as 10 g, 30 g, 45g, 50 g, 55 g, 70 g,
488 100 g, 120 g, and 150 g for the estimation of optimum micro-sized particles in the absorber basin. The mPCM
489 samples were prepared with different weight% of Borassus Flabellifer Micro-Sized Particles such as 5, 10, 15
490 and 20 wt%, impregnated in the paraffin wax for better thermal conductivity. Two solar stills were developed
491 and the experimentations were carried out during September 2021. The two solar stills were solar still with 50 g
492 palm flower powder in the absorber basin, 20wt% mPCM as thermal storage materials (PCMPFP-SS) and CSS.
493 The overall yield of PCMPFP-SS was compared with CSS. The thermal, environmental and economic analysis
494 was evaluated for PCMPFP-SS and CSS.
495 The conclusion from the present study are:

- i. The inclusion of optimum weight of palm flower powder in the absorber basin enhanced the evaporation resulting in more yield than CSS. The optimum weight of palm flower powder-micro sized in the absorber basin was 50 g.
- ii. The increase in productivity with different weight of palm flower powder such as 10 g, 30 g, 45g, 50 g, 55 g, 70 g, 100 g, 120 g, and 150 g were 11.85 %, 24.78 %, 36.10 %, 37.25 %, 36.80 %, 34.35 %, 33.05 %, 10.25 % and -20.22 % respectively.
- iii. The mPCM with maximum thermal conductivity was obtained at 20 wt% of palm flower powder impregnated in the PCM-paraffin wax. The thermal conductivity of 20 wt% mPCM was 57.14 % higher than pure paraffin wax.
- iv. The yield for PCMPFP-SS was 4670 ml/m²-day, 4250 ml/m²-day on day 1 and day 2 respectively, whereas yield for CSS was 3030 ml/m²-day, 2800 ml/m²-day on day 1 and day 2 respectively. The increase in productivity for PCMPFP-SS was 54.12 % and 51.78 % on day 1 and day 2 respectively.
- v. The thermal analysis results showed that the efficiency of PCMPFP-SS was 42.59 % on day 1 and 39.57 % on day 2 whereas the efficiency of CSS was 27.68 % on day 1 and 26.07 % on day 2.
- vi. The economic analysis results revealed that the CPL for PCMPFP-SS and CSS were \$ 0.025 and \$ 0.032 respectively. The payback period of CSS was 5.1 months whereas for PCMPFP-SS the payback period was 4.1 months.
- vii. From the environmental analysis, it was found that the total embodied energy associated for PCMPFP-SS and CSS was 829.1 kWh and 756.4 kWh respectively, whereas the carbon credit gained for PCMPFP-SS was 211.6 \$ and for CSS it was \$ 133.56.

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527 **Arivazhagan Sampathkumar:** Conceptualization, Formal analysis, Investigation, Data Curation, Writing –
528 Original Draft.

529 **Sendhil Kumar Natarajan:** Conceptualization, Validation, Resources, Writing- Review & Editing,
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