Dispersed solar still for effective desalination using montmorillonite nanoparticles for sturdy clean water yield
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ABSTRACT

Direct Solar Steam Generation (DSSG) system is an emerging technique in the field of desalination for yielding sustainable clean water. This investigation propagates through the use of nanoscale absorbers (montmorillonite) for sturdy desalination because of their excellent photo thermal conversion of nanoparticles. The solar absorber was dispersed in sea water in liquid type rather than fixed or floating type. Nanoparticles of chemical composition were employed by the researchers from starting to the present day, which includes carbon nanotubes, graphene oxide, etc., Inspired by nature and keeping in mind an eco-friendly technique, here we considered montmorillonite clay nanoparticles of natural origin. The experiment was conducted for an operational period of 14 days with a yield of 5.33–6.45 kg/m\textsuperscript{2}/day with an evaporation rate of 0.70, 1.42 and 4.47 kg/m\textsuperscript{2}/hr under 1-, 2- and 4-sun irradiance. The clean water output parameters was validated with WHO standards to satisfy potable water characteristics. The water characteristics before desalination for turbidity, pH, and Cl\textsuperscript--, Na\textsuperscript+ and TDS were found to be 48.50, 8.7, and 18,400, 12,120, 20,400 mg/L respectively; after desalination they were found to be 0.30, 6.65, 12, 4.5 and 52 mg/L respectively. This work focuses on current water scarcity problem and suggest a way to survival by using naturally available, low cost material.

Key words | clean water, desalination, direct solar steam generation, dispersed solar still, montmorillonite, nanoscale absorber

HIGHLIGHTS

- A novel SSG mechanism by montmorillonite replacing carbon constituent compounds.
- A low cost, stable method affordable by people belonging to lower economic standards.
- A sustainable technique by the natural resources.
- An additional process required in chemical based nanoparticles technique, but no further treatment for the natural based nanoparticles.

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INTRODUCTION

One way to solve the water shortage problems in coastal areas is to include low cost, sustainable and eco-friendly materials in the desalination process. Montmorillonite is one of the materials that is used in a wide range of applications due to its capacity for excellent photo thermal conversion. Montmorillonite can strongly transform absorbed solar light into thermal energy and evaporation of water with sunlight. Solar steam generation helps in accelerating the water-air interface with montmorillonite in this process.

Using direct solar steam generation (SSG), water was produced and the article reviews different types and principles of SSG such as solar thermal conversion material fixed at the bottom, solar thermal conversion material floating on the surface and solar thermal conversion material dispersed in liquid. The mechanism of the water evaporation rate and the strategy involved in the SSG method is also discussed. Storer et al. (2020) used the SSG principle with the help of graphene oxide, rice straw and aerogel to produce clean water. The energy conversion efficiency achieved for 88.9% under one-sun irradiation. Therefore, the principle of SSG can be used to perform with different types of nanomaterials thereby evaluating the performance and efficiency of those nanomaterials.

The physical and chemical properties of rice straw have been investigated (El-Sayed & El-Samni 2006; Alcántara et al. 2020; Goodman 2020). The results show that rice straw was with 65.92% Silicon-di-Oxide, which was employed in the production of clean water using SSG. Chemical-based nanoparticles were used to increase the productivity of the work in some studies (Gupta et al. 2016; Bait & Si-Ameur 2018; Ghaefurian et al. 2020).

Rice straw was used to produce clean water by calculating the evaporation rate (Chang et al. 2014; Elmolla et al. 2016; Fang et al. 2019; Gan et al. 2019; Zhu et al. 2019). Yaacab et al. (2016) used paddy straw in powdered form as filler in polyactic acid and also studied the thermal properties of paddy straw. Shao et al. (2015) used rice straw sludge which was treated further and used as manure in agriculture.

Balachandran et al. (2019) used Fe2O3 nanoparticles in a solar still for the enhancement of thermal conductivity, which in turn increased the rate of evaporation resulting in increased efficiency with additional output. Shanmugan et al. (2018) used Al2O3 nanoparticles along with C18H36O2 in a solar still. The efficiency of their solar still was about 59.14% higher compared to other similar solar stills enhanced by Al2O3 nanoparticles.

Winfred Rufuss et al. (2017) used the nanoparticle CuO which is a Phase Change Material in an area of 0.5 m² at an inclination of 13°. The intensity of solar radiation of 830 W/m² was used in the solar still in the operation which yielded 2.64 kg/0.5 m². This shows a 35% increased output compared to a conventional still. Kabeel et al. (2020) used graphene oxide nanoparticles in a tubular still. The productivity was observed to be 5.62 kg/m², which was 116.5% greater when compared with conventional efficiency. Liu et al. (2018) used graphene oxide nanoparticles in SSG for the purpose of treating sea water.

Nanofluids like Al2O3 or graphene methanol were used instead of the nanoparticle CuO (Goshayeshi & Safaei 2019; Olia et al. 2019; Safaei et al. 2019; Sarafraz & Safaei 2019; Yeping et al. 2019; Maithani et al. 2020). Here they also adopted stills of different geometry for the purpose of desalination.

Advanced technologies are employed in the desalination process in this decade, more like nanofluids based solar cooling for the production of hydrogen (Toghyani et al. 2019; He et al. 2020). Some other articles related to the work were also studied for reference purposes (Strang 2020; Bagheri et al. 2021; Maru et al. 2021).

Desalination was performed using a single slope solar still and the experiment was conducted by varying the parameters and different sets of nanoparticles (Rashidi et al. 2017, 2018a, 2018b, 2018c, 2018d, 2019). With this, they had analysed the performance of the still with these parameters.

Osorio-Ruiz et al. (2017) used jatropha and soybean meal along with montmorillonite clay and prepared a protein film with the help of the casting method. Here, the water vapor transmission rate was recorded as 4.8 g/hr/m². Kang et al. (2010) studied the photo-degradation of aqueous methyl orange catalyzed by P25 and it was examined in the presence of montmorillonite clay. This investigation was performed to determine the effect of clay on the
photocatalytic activity of P25. From the above two papers it is clear that montmorillonite clay has higher capacity to absorb thermal radiation and it helps to increase the evaporation rate. Baskaran & Saravanane (2020) used montmorillonite for the partial treatment of sea water. This work used the mechanism of adsorption and cation exchange that shows us the capacity of montmorillonite in reducing the salinity of sea water. Here, it is evident from the review of this paper that montmorillonite has excellent adsorption properties. Montmorillonite clay nano-powder has 65.34% SiO₂ by weight. Therefore, it is clear that montmorillonite clay nano-powder can be used to enhance the thermal properties.

As discussed above, montmorillonite was chosen for its SiO₂ content, and it was evident that from 1995 to 2020 the nanoparticle used in clean water production was mostly carbon based, i.e. chemical elements such as Al₂O₃, C, CNTs, Cu, CuO, Cu₂O, Fe₂O₃, GO, GNP, SiC, SiO₂, SnO₂, TiO₂ and ZnO were used. These chemicals have traceable and higher amounts of montmorillonite clay which is a natural material. So, this work aims to replace these chemicals with montmorillonite aiming to achieve low-cost, enhanced thermal capacity, increased evaporation rate and significantly decrease environmental pollution. The work with Montmorillonite Nanoparticle-based Dispersed Solar Still (MMNP-DSS) using SSG for sea water desalination reports that montmorillonite has excellent thermal conversion capacities, can transform absorbed solar radiation into thermal energy, and has the ability to increase the evaporation rate.

In the long run, it also prevents land subsidence caused by over-extraction of ground water. Strict adherence to conservative ground water policies will lead to preservation of ground water aquifers. Biodesalination is one of the emerging methods of desalination as it is ecofriendly. Mankind is entitled to use only surface water and not subsurface/groundwater which is the birthright of trees and plants. Therefore, this article considers treating sea water for domestic usage. With the rapid rise in population and rapid decline in freshwater sources, this research will form the basis of relevant rules and laws in future restricting citizens from over-utilization of groundwater and the cost-effective utilization of sea water. In addition, this method is eco-friendly by reducing environmental pollution and is a sustainable method for the conversion of sea water into fresh water.

**EXPERIMENTAL SECTION**

**Materials**

Montmorillonite clay was purchased from the Geotechnical Laboratory of Pondicherry Engineering College (Puducherry, India) (12.0096°N, 79.8549°E); the cost of montmorillonite clay is Rs. 100 for 100 g. The obtained clay sample was further converted into nano-size by means of the ball milling process. In the milling process, the clay powder (Figure 1) was loaded in the milling setup and run at a speed of 300 rpm for 24 hours. The density and particle size of montmorillonite clay was 3 g/cm³ and 70 nm, respectively. The instruments used for the investigation are shown in Table 1. The particle size distribution profile is shown in Figure 2. It was plotted with the weight of particles against the particle size (probability), and the particle size distribution graph is obtained. The surface area of the montmorillonite clay was calculated based on Diamond & Kinter (1956) as:

\[
\text{Total Surface Area (m}^2/\text{g}) = (2241/L) + 754 = 754 \text{ m}^2/\text{g}
\]

where L is the size of the nanoparticle.

![Figure 1](https://example.com/figure1.jpg) | Digital image of montmorillonite clay nanoparticle.
Sea water samples with 3.5% salinity were collected from Pillaichavadi, Puducherry, Bay of Bengal (12.0096°N, 79.8549°E). The sample collecting container was chosen with respect to the UNEP/WHO (1996) standard, Chapter 5.

Instrumentation

The uncertainty analysis of the instruments in the experiments, viz. solar pyranometer and thermometer, were found to be 1.72 and 3.71%, respectively. This uncertainty was statistically calculated using the following equation:

\[
    u = \left[ \left( \frac{\partial S_1}{Z_1} u_1 \right)^2 + \left( \frac{\partial S_2}{Z_2} u_2 \right)^2 + \ldots + \left( \frac{\partial S_n}{Z_n} u_n \right)^2 \right]^{1/2}
\]  

Characterization

The microstructures and morphology of the montmorillonite clay nanoparticles were characterized using a scanning electron microscope (SEM), Hitachi model S-3400N. SEM analysis helps in getting us to study the montmorillonite clay nanoparticle soil facilitating. The observations provided very fine details and good focus over a wide range of the specimen surface of the nanoparticle. The SEM analysis was performed in the Central Instrumentation Facility, Pondicherry University, Puducherry. Figure 3 shows the SEM analysis of montmorillonite clay nanoparticles, which was attached as the supporting document. SEM analysis shows that the particle shape and size distribution will result in increased thermal enhancement. Therefore, this in turn helps to thrive towards achieving greater efficiency.

Solar steam generation experiments (MMNP-DSS)

Sea water (100 mL) with a salinity of 3.5% was collected in a 250 mL beaker. To this optimized substance, 10 g of montmorillonite nanoparticle (MMNP) was added and mixed with a magnetic stirrer at a speed of 300 rpm to achieve a homogenous mixture. The experiments were conducted at room temperature (27 ± 1°C) and humidity of 40 ± 10%.
The prepared MMNP-DSS was placed in a circular container. The whole apparatus was covered to prevent the escape of evaporated water and to facilitate the collection of condensed water. Steam generation experiments were performed using a solar pyranometer instrument to simulate the solar-irradiance and mass change of the evaporated water was recorded at different time intervals using an electronic balance. The quality parameters were validated with IS 10500-2012 (2012).

An outdoor solar distillation unit was assembled with an inlet container, as shown in Figure 4. The inlet container was supplied with a sample of sea water, which was connected to the Montmorillonite Nano Particle – Dispersed Solar Still System (MMNP-DSS). The experiment was carried out for a period of 2 weeks to study stability and durability and to maintain the evaporation efficiency in a stable manner. The collected distillate water before and after the experiment was analyzed for the presence of ions as per APHA, AWWA, WEF (2012).

RESULTS AND DISCUSSION

Excellence of MMNP-DSS

The saline water was dispersed with MMNP throughout since the nanoparticles had excellent photothermal conversion. This enables a rapid increase in temperature on the surface of nanoparticles, reaching above boiling point of the liquid water when exposed to sunlight. Then the vapor forms a thin layer of steam at the nanoparticle–liquid interface. With continuous solar illumination, the vapor wrapped on the nanoparticle rises to the liquid–air interface, releasing vapor and returns back to the state of liquid water. MMNP’s surface acts as a boiling nucleation site helping in the repetition of the vaporization process. The solar driven heating...
of the nanoparticles produces a high temperature steam directly while huge heat transfers from the returning vapor.

The experiment was operated under 1-sun illumination for evaluating the performance. The mass change of the sea water (3.5% salinity) was recorded. Figure 5 shows the evaporated water versus time which explains the mass changes of evaporated water in the pure water and keeps the pure water as a reference for comparison with 10 g MMNP-DSS dispersed samples. Zero order kinetic equation was considered for modelling the water evaporation process as:

\[ m - m_0 = -kt \]  

where \( m \) is the actual water mass at time \( t \); \( m_0 \) is the initial water mass; and \( k \) is the water evaporation efficiency.

The water evaporation efficiency of the MMNP-DSS 10 g was calculated for 1-, 2- and 4-sun solar irradiation with pure water as the reference medium. The irradiation MMNP-DSS 10 g were 0.7, 1.42 and 4.47 kg/m² h for the corresponding 1-, 2- and 4-sun solar irradiation and the water evaporation efficiency of pure water were 0.26, 0.38 and 0.71 kg/m² h for the corresponding 1-, 2- and 4-sun solar irradiation. The efficiency increased by 2.69, 3.73 and 6.29 times with respect to the corresponding one-, two- and four-sun solar irradiation in the MMNP-DSS when it was compared with the efficiency of the reference pure water. The increase in efficiency of the MMNP-DSS mix was due to the addition of montmorillonite clay nanoparticles that enabled a rapid increase of temperature in the liquid-nanoparticle interface leading to a faster rate of evaporation in the liquid-air interface. Figure 6 shows the comparison of the water evaporation rate and solar illumination for 1-, 2- and 4-sun solar irradiation of pure water and MMNP-DSS 10 g sample.

This research was compared with other related works of this kind. Fang et al. (2019) used photothermal material (carbonized rice straw) under 1-sun solar intensity in the SSG and obtained a water evaporation rate of 1.2 kg/m² h. Gan et al. (2019) experimented with SSG of floating solar still type, using CNT’s, and obtained a water evaporation rate of 0.88 kg/m² h. This current work has an efficiency of 0.7 kg/m² h for 1-sun solar irradiation (Figure 5). Although the efficiency of this work was low when compared to the results of Fang et al. (2019) and
Gan et al. (2019) for 1-sun irradiation, the efficiency for the increased interval of solar irradiation of this work with MMNP-DSS shows a significant increase, nearly at 4-sun irradiation. The reference work has higher efficiency initially due to the presence of a carbon element which helps in the evaporation rate. On the other hand, in MMNP-DSS, it shows increased efficiency for the increased level of irradiation due to natural silica-based material which helps in rapid evaporation with time bound and it also operates for long time and is also a steady process in terms of efficiency. Also, this process with MMNP-DSS was eco-friendly by reducing pollution.

**MMNP-DSS sturdy clean water yield**

The outdoor desalination experiment was carried out for 14 days under natural solar radiation as shown in Figure 4. The experimental setup details, which are explained above in the experimental section, records the ambient temperature and weather for the corresponding 14 days operational period. The experiment was performed between 8.00 am and 6.00 pm, i.e. for approximately 10 hours per day. The sturdy clean water yield was in the range of 5.33–6.45 kg/m²/day. The collected clean water was tested as per APHA AWWA WEF (2015) and validated with WHO and Indian Standards 10500:2012. Figure 7 shows the yield of clean water during the 14 days operational period. The ambient temperature of 38 °C showed a yield of 6.45 kg/m²/day on day 8, which is the maximum among the other operational days. The MMNP-DSS, which creates a high temperature interface, increases the rate of evaporation which withholds the temperature received during daytime and making it used for the post day time. The ambient temperature of 32 °C showed a yield of 5.33 kg/m²/day on day 6, which was the minimum among the other operational days where the climate was cloudy.

**Validation of water quality**

Figure 8 shows a comparison of chemical characteristics before and after desalination, and the results were validated with WHO standards and Indian Standards 10500:2012 as in Table 2. The initial and final turbidity in the laboratory test as of APHA AWWA WEF (2015) was 48.50 and 0.30 mg/l. The collected clean water was tested as per APHA AWWA WEF (2015) and validated with WHO and Indian Standards 10500:2012. Figure 7 shows the yield of clean water during the 14 days operational period. The ambient temperature of 38 °C showed a yield of 6.45 kg/m²/day on day 8, which is the maximum among the other operational days which means that over the 14 operational days, the yield was only maximum on day 8. The MMNP-DSS, which creates a high temperature interface, increases the rate of evaporation which withholds the temperature received during daytime and making it used for the post day time. The ambient temperature of 32 °C showed a yield of 5.33 kg/m²/day on day 6, which was the minimum among the other operational days where the climate was cloudy.

**Figure 7** Sturdy clean water yield in the outdoor experiment from day 1 to day 14.

**Figure 8** Chemical characteristics before and after desalination.
NTU, respectively. The initial and final pH in the laboratory test was 8.70 and 6.65 (APHA AWWA WEF 2012). The ion concentration for sodium (Na<sup>+</sup>) and chloride (Cl<sup>−</sup>) initially were 12,120 and 18,400 mg/L, respectively. The ion concentration for sodium (Na<sup>+</sup>) and chloride (Cl<sup>−</sup>) after the desalination process was observed to be 4.5 and 12 mg/L, respectively. Finally, the total dissolved solids (TDS) concentration of the sample before and after experimentation was 20,400 and 52 mg/L.

The results were validated for sodium (Na<sup>+</sup>) and chloride (Cl<sup>−</sup>) because they form the major composition in sea water and other ions were in negligible amounts which would automatically be reduced with a decrease in sodium (Na<sup>+</sup>) and chloride (Cl<sup>−</sup>) ions. The output distillate was significantly reduced to 99.38% in turbidity, 99.96% in sodium (Na<sup>+</sup>), 99.93% in chloride (Cl<sup>−</sup>) and 99.74% in TDS due to the use of MMNP-DSS 10 g. The pH also reduced to a value which is good for drinking as of validation with WHO and Indian Standards. So, it is advisable from this point to adopt MMNP-DSS in coastal regions for desalination purposes which undoubtedly provides a sturdy clean water yield through solar steam generation.

### CONCLUSIONS

The MMNP-DSS based SSG experimental investigation summarizes that montmorillonite clay nanoparticles have high thermal conductivity, which also increases the rate of evaporation. Hence, it is concluded that this novel experimentation used montmorillonite nanoparticles as a solar thermal absorber apart from previous usage by the researchers for its chemical-based nanoparticles. The experiment was conducted for an operational period of 14 days with a sturdy clean water yield of 5.33–6.45 kg/m²/day with an evaporation rate of 0.70, 1.42 and 4.47 kg/m²·hr under 1-, 2- and 4-sun irradiance, respectively. In addition, from the results it can be revealed that the evaporation rate in the later stage of the day also seems to be stable which is stabilized by the thermal holding capacity of montmorillonite. The sediment obtained in the experiment in the later stages was disposed of by making manure for agricultural fields. In coastal regions, the MMNP-DSS could also increase the socio-economic standards in that area. The structure and operation was so simple and it is also an eco-friendly method which can be carried out at an affordable cost, even by the people of low economic standards.

### DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

### REFERENCES


IS 10500-2012 2012 Drinking water standards, India.


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