VNU Journal of Science: Earth and Environmental Sciences, Vol. 40, No. 1S (2024) 74-82

VNU Journal of Science: Earth and Environmental Sciences

Journal homepage: https://js.vnu.edu.vn/EES

Original Article

Efficiency of Optimized Fabrication Process for Light-absorbing Membranes from Sewage Sludge Applied in Solar-driven Steam Generation Systems

Dang Thi Hai Linh[1,*], Nguyen Duc Binh[2], Nguyen Thi Hanh[1], Pham Thu Huyen[1], Doan Thi Nhat Minh[1,3], Nguyen Duy Tu[1], Dao Van Duong[4]

[1]*Faculty of Environmental Sciences, VNU University of Science, 334 Nguyen Trai, Thanh Xuan Hanoi, Vietnam*

[2]*Dankook UNI - Jukjeon Campus, 152 Jukjeon-ro, Suji-gu, Yongin-si, Gyeonggi-do, Korea*

[3]*Instituto Universitario de Investigación en Gestión Forestal Sostenible (iuFOR), ETSIIAA, Universidad de Valladolid, Palencia, Spain*

[4]*Phenikaa University, Yen Nghia, Ha Dong, Hanoi, Vietnam*

Received 30 July 2024
Revised 22 September 2024; Accepted 23 October 2024

Abstract: Solar-driven evaporation systems have been studied to provide clean water, especially for islandic areas. Carbon materials made from sludge in domestic wastewater treatment plants have been studied to produce light-absorbing membranes in solar-to-steam (STS) systems. However, the technical limitation of this method is that the water evaporation rate is still low. In this study, the process of manufacturing light-absorbing membranes was optimized to simplify the process while increasing the water evaporation rate and testing the application of converting seawater into fresh water. The optimal evaporation rate was 2.65 $kg.m^{-2}.h^{-1}$, higher than the system using vacuum drying membranes (1.88 $kg.m^{-2}.h^{-1}$) under 0.6 kW/m^2 illumination conditions. When illuminated, the surface temperature of the TN_0.1 light-absorbing membrane reached 36.5°C, meaning 2.5°C higher than that of the reference membrane (without carbon material). The results of analyzing some anion and cation indicators in the harvested water showed that the fabricated STS systems could be applied well to convert seawater into fresh water for domestic use. Especially, the treatment efficiencies for Na^+, $Ca^{2+}, Cl^-, NO_3^-, and\ SO_4{}^{2-}$ reach 99.87%, 94.35%, 99.5%, 99.98%, and 99.44%, respectively.

Keywords: Solar-driven steam generation systems, water evaporation, fresh water, sewage sludge, carbon material.

* Corresponding author.
E-mail address: linhdth@hus.edu.vn

https://doi.org/10.25073/2588-1094/vnuees.5204

1. Introduction

Population growth, socio-economic development, and the global scarcity of fresh water are exacerbating the conflict between water supply and demand. It is projected that approximately 5 billion people worldwide will face difficulties accessing safe drinking water by 2050 [1-3]. To address this issue, it is essential to deploy effective, environmentally friendly, and cost-efficient technologies for seawater desalination and wastewater treatment. Among these, solar-to-steam technology has been extensively utilized for desalinating seawater, generating electricity, and water treatment [4]. For optimal performance, solar-driven steam generation systems must efficiently convert solar radiation into thermal energy, ensure a suitable water transport rate, and effectively remove salts during STS process [5, 6]. In solar-driven steam generation systems, the key component is the photothermal materials [7-10]. Number of materials, such as metal nanoparticles [11], semiconductors [12], and carbon nanomaterials [13], have been investigated for use as photothermal materials. Additionally, various porous materials, such as aerogels [14] and foam membranes [15], have been developed as carriers for photothermal materials to enhance evaporation efficiency. Among photothermal materials, carbon-based materials have shown outstanding properties, including broad solar absorption, high photothermal conversion efficiency, and relative durability and stability under environmental conditions such as low temperatures and high humidity... [16]. Research on fabrication of light-absorbing membrane derived from waste sludge applied in STS systems has attracted attention due to their potential for efficient water purification [17]. Dang Linh et al. (2023) have focused on designing and applying these light-absorbing membranes on solar-driven evaporators [17]. By utilizing readily available and low-cost waste sludge materials, these light-absorbing films provide a sustainable and cost-effective solution for producing potable water from various sources, including seawater and polluted water. This method is particularly significant in areas facing freshwater scarcity, such as island regions or areas with contaminated water sources.

The study by Dang Linh et al. (2023), demonstrated the feasibility and significant potential of using sludge from urban wastewater treatment plants in the fabrication of light-absorbing membranes for solar-driven steam generation [17]. However, the fabricated membranes exhibited several limitations, including the presence of cracks and a relatively low water evaporation rate, which reached only 1.88 $kg.m^{-2}.h^{-1}$ at best. In response to these challenges, our study has optimized the membrane fabrication process by employing natural drying under ambient conditions to reduce energy consumption and enhance performance. As a result, the water evaporation rate increased to 2.65 $kg.m^{-2}.h^{-1}$ Additionally, we tested the membrane's application in recovering fresh water from seawater.

2. Methods

2.1. Fabrication of Light-absorbing Membranes from Wastewater Sludge

Table 1. Membranes

Material mass (g)	Vacuum drying [15]	Natural drying
0	SK_0.00	TN_0.00
0.05	SK_0.05	TN_0.05
0.06	SK_0.06	TN_0.06
0.07	SK_0.07	TN_0.07
0.08	SK_0.08	TN_0.08
0.09	SK_0.09	TN_0.09
0.1	SK_0.1	TN_0.1

The light-absorbing membranes (as specifically presented in Table 1) were produced following the treatment process outlined in Figure 1. Specifically, sludge was collected at the Kim Lien domestic wastewater treatment station, then dried and calcined at 500 °C for 2 h to obtain carbon material. The carbon material was then milled under dry conditions for 3 h, followed by ultrasonic vibration for 30 min.

Following vacuum filtration, the resulting membranes were naturally dried under ambient conditions, rather than employing the vacuum drying process used in our previous study [17]. Different carbon material masses (Table 1) will be investigated to obtain the optimum membrane.

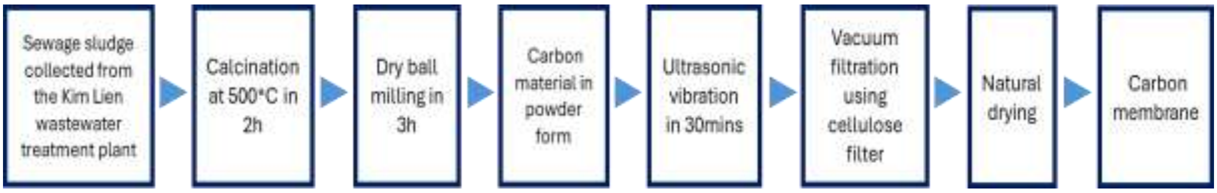

Figure 1. Membrane fabrication process.

2.2. Characterization of Membranes

After synthesis, the membranes were analyzed for their morphological characteristics using scanning electron microscopy (SEM). This investigation was carried out at the Key Laboratory of Advanced Materials for Green Growth at VNU University of Science, Hanoi (KLAMAG).

2.3. Evaporation Rate Evaluation

The evaporator is designed as in Figure 2, based on the research by Dang Linh et al. (2023) [17]. Sunlight simulator is 94023A SOLAR SIM S/N 547 – NEWPORT and this experiment was conducted in the renewable energy conversion and storage laboratory at Phenikaa University.

The evaporation rate is calculated according to formula (1) as follows:

$$v = \frac{W\ loss}{A.t} \quad (1)$$

With:

v: evaporation speed of water ($kg.m^{-2}.h^{-1}$);

W_{loss}: Amount of water lost during steam generation (kg);

A: area of the illuminated part (m^2);

t: Evaporation time (h).

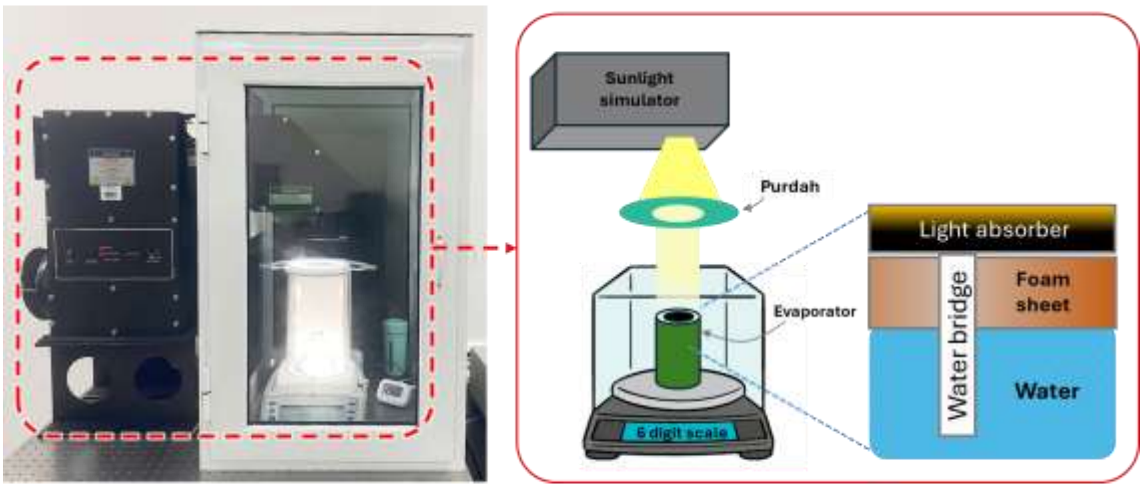

Figure 2. Structure of solar-driven steam generation systems and sunlight simulation system [18].

2.4. Water Harvesting Methods

The evaporator was placed inside a spherical plastic cap on a round glass dish containing the harvested water [18]. The experiment used a sunlight simulator system as the light source for the water evaporator under conditions of 25 °C room temperature, 65% humidity, and 0.6

kW/m^2 irradiation (0.6 Sun). Actual seawater was used as the input water for the water harvesting experiment.

2.5. Surface Temperature Investugation

The temperature of the TN_0.1 light-absorbing membrane surface and reference membrane (without cacbon material) under illuminated conditions was investigated using a TESTO 875i infrared thermography camera.

2.6. Water Quality Assessment

In this study, water samples before and after harvesting were analyzed using ICP-OES (iCap PRO X DUO) at the Environmental Research Laboratory, Faculty of Environment, and ion chromatography at the Analytical Chemistry Laboratory, Department of Chemistry, University of Natural Sciences.

3. Results and Discussion

3.1. Results of Fabricating Membranes

In the previous study, carbon materials were successfully fabricated with key characteristics, including a high carbon content (50.66%), a specific surface area of 63.74 m^2/g, and the presence of numerous surface functional groups (O-H, C-C, C=C, C-O), making them suitable for use as light-absorbing materials in water evaporators [17]. However, when using vacuum drying for the fabrication of light-absorbing films, the highest recorded water evaporation rate was only 1.88 kg.m^2.h^{-1}. To address this, the current study replaces the vacuum drying process with natural drying to reduce the energy consumption during film fabrication. The newly fabricated films will be applied in water evaporators to assess their evaporation rates and evaluate their potential for producing fresh water from seawater.

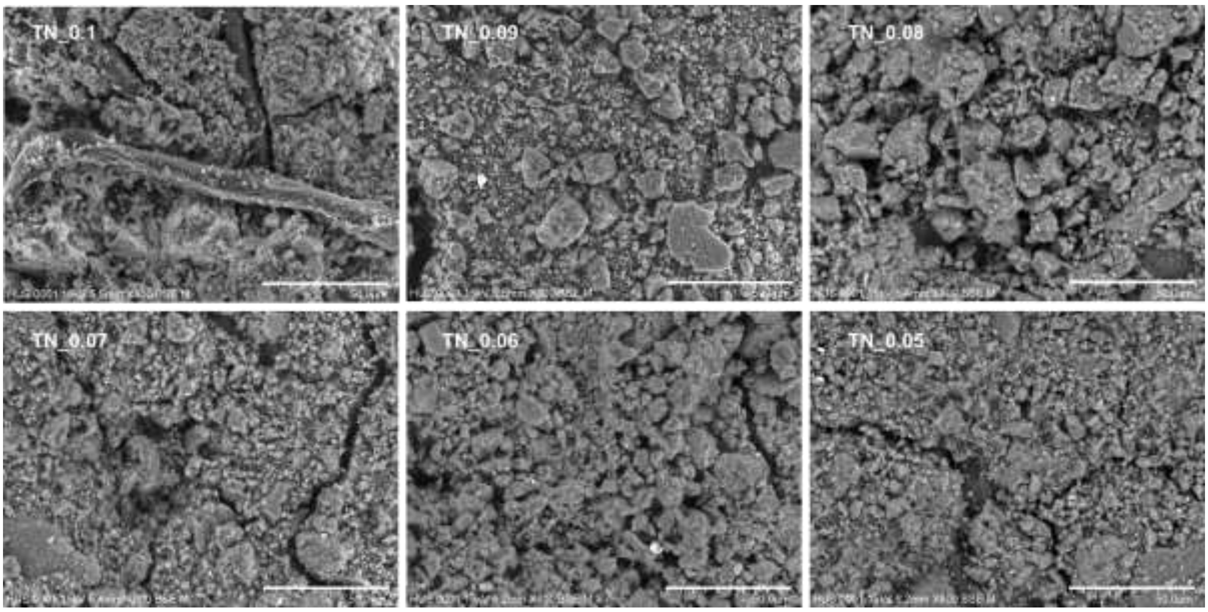

Figure 3. SEM image of naturally dried membranes.

The light-absorbing carbon membrane was successfully fabricated following the process presented in Figure 1. Surface morphology analysis of the membrane under different fabrication conditions is shown in Figure 3, which will compare with our previous results in [17]. SEM results indicate a relatively even dispersion of carbon materials on the cellulose membrane. However, the vacuum-dried membrane shows more material accumulation and cracks compared to the naturally dried sample. Carbon material is introduced to cellulose by physical bonds. It can be seen from Figure 3 and Figure 4, the material particles are attached to the cellulose fibers and evenly distributed throughout the entire cellulose membrane. Therefore, the evaporation efficiency of the vacuum-dried sample is predicted to be lower than that of the naturally dried sample.

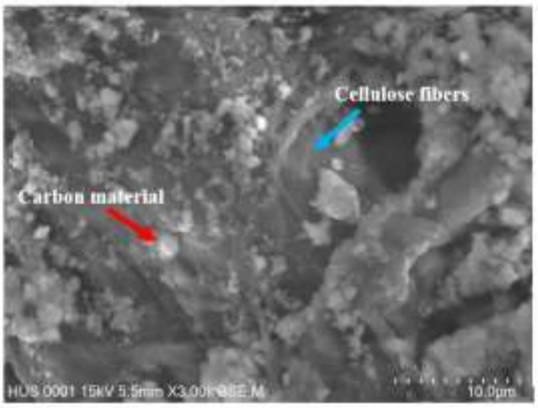

Figure 4. SEM image of TN_0.1 membrane.

3.2. Water Harvesting Ability of Solar-driven Steam Generation Systems

3.2.1. Evaporation Rate of the Membranes

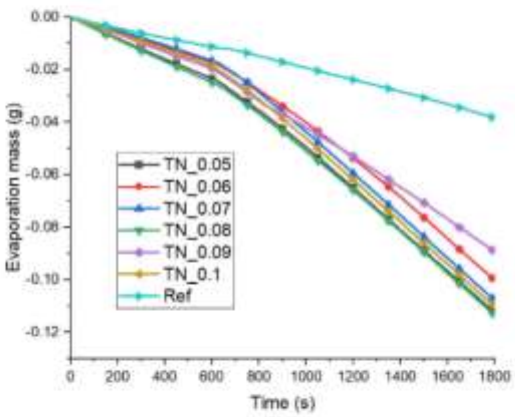

Figure 5. Evaporation mass changing by the time.

The evaporation mass of water over time is presented in Figure 5. It is evident that under illumination (from 600 s to 1800 s), the evaporation mass of the STS generators with BHNT material membranes is significantly higher than that of the control sample (membrane without carbon material). This can be attributed to the carbon material's ability to absorb solar energy, convert it into heat, raise the temperature of the evaporation membrane, and thereby enhance the water evaporation process of the device.

The water evaporation rates of water evaporators using different light-absorbing membranes under “light-on” and “light-off” (dark) conditions are shown in Figure 6 and Table 2. The results demonstrate that, under illuminated conditions, the water evaporation rate of water evaporators using light-absorbing membranes manufactured under natural drying conditions is significantly higher compared to when not illuminated. The evaporation rates of all solar-driven steam generation systems with different light-absorbing membranes are summarized and shown in Figure 6. The water evaporator using TN_0.1 membrane has the highest evaporation rate, reaching 1.23 $kg.m^{-2}.h^{-1}$ under light-off conditions and 2.65 $kg.m^{-2}.h^{-1}$ under light-on conditions. Meanwhile, the highest evaporation rate recorded for the vacuum-dried samples was 1.14 $kg.m^{-2}.h^{-1}$ under light-off conditions and 1.88 $kg.m^{-2}.h^{-1}$ under light-on conditions [14]. Evaporators using light-absorbing membranes manufactured under natural drying and vacuum drying conditions have higher evaporation rates compared to blank samples (membranes without carbon materials), which have an evaporation rate of only 0.92 $kg.m^{-2}.h^{-1}$ under light-on conditions. This result illustrates that incorporating carbon materials into light-absorbing membranes and optimizing the manufacturing process can enhance the water harvesting productivity of STS systems. Table 3 shows that the light-absorbing membrane fabricated from sewage sludge has high potential for application in solar water evaporation systems with relatively high water evaporation rates compared to other studies (under illumination conditions of less than 1 Sun).

Table 2. Evaporation rate data for naturally dried samples

Naturally dried samples (g)		TN_0.05	TN_0.06	TN_0.07	TN_0.08	TN_0.09	TN_0.1
Naturally dried samples	light-off	0.8	1.09	1.12	0.44	0.51	1.23
	light-on	2.38	2.46	2.6	1.0	2.14	2.65

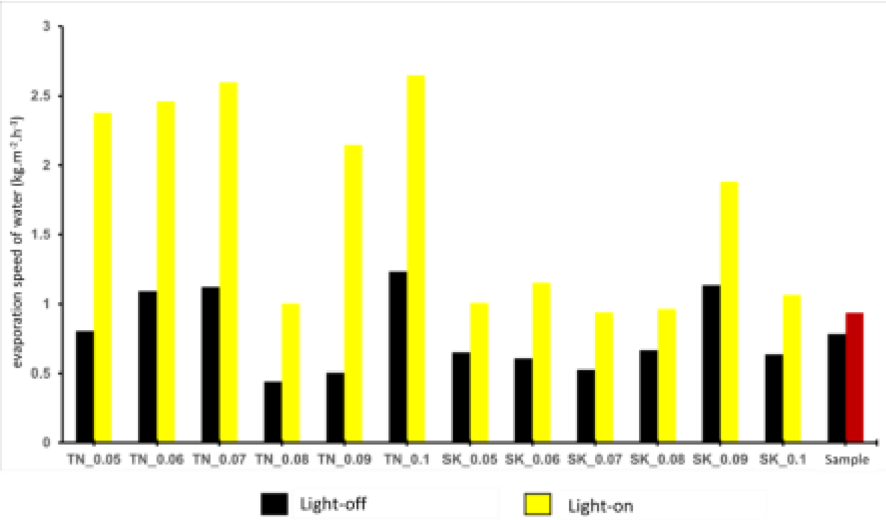

Figure 6. Comparison of water evaporation rates from evaporators.

Table 3. Comparison of Water Evaporation Rates in Solar Water Evaporation Systems with Different Light-Absorbing Materials

STT	Material	Illumination Intensity	Evaporation Rate	Ref
1	F-Wood/CNT	1 Sun/36, 28 °C	0.95 $kg.m^{-2}.h^{-1}$	[18]
2	Enteromorpha prolifera	<1 Sun	1.1−1.3 $kg.m^{-2}.h^{-1}$	[19]
3	Carbonized carbon dots-modified starch aerogel	≤1 Sun	2.29 $kg.m^{-2}.h^{-1}$	[20]
4	Carbon material from Reeds	1 Sun	2.42 $kg.m^{-2}.h^{-1}$	[21]
5	Sludge from domestic wastewater treatment plants (Vacuum Drying Process)	0,6 Sun, 25 °C, 65% humidity	1.88 $kg.m^{-2}.h^{-1}$	[17]
6	Sludge from domestic wastewater treatment plants (Natural Drying Process	0,6 Sun, 25 °C, 65% humidity	2.65 $kg.m^{-2}.h^{-1}$	This study

3.2.2. Temperature of Evaporation Membranes

To assess the role of carbon material membranes in solar-driven water evaporation systems, the surface temperature of the light-absorbing membrane was examined under illumination conditions, as shown in Figure 7. The highest temperature recorded for the membrane containing carbon material was 36.5 °C which is higher than the temperature of the control membrane (34 °C). This indicates that the carbon material plays a role in absorbing solar radiation and converting it into heat, thereby increasing the surface temperature and enhancing the water evaporation rate of the system.

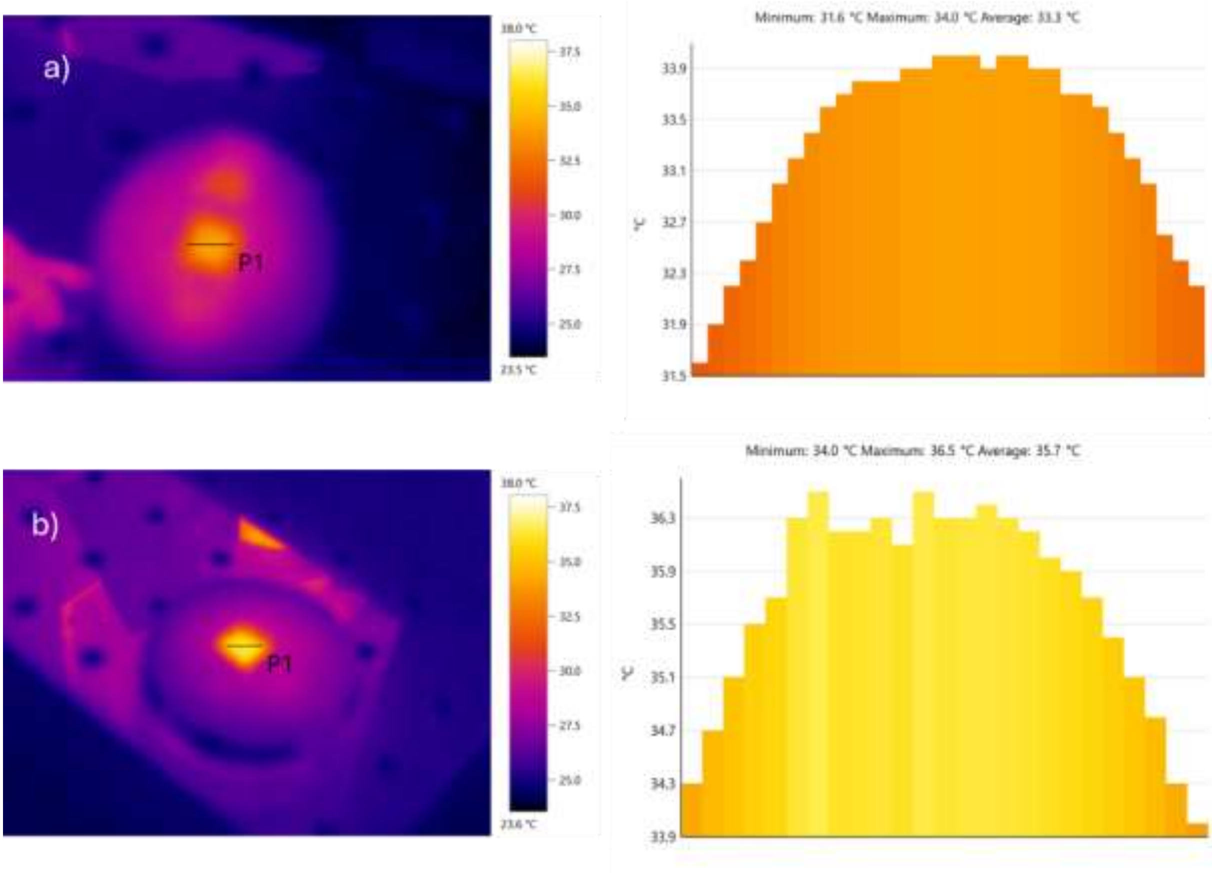

Figure 7. Surface temperature of light absorption membrane (a) with and (b) without cacbon material in light-on condition.

3.2.3. Quality Evaluation of Harvested Water

The results from the analysis of anion of input water samples and harvested water samples using an ion chromatograph are presented in Table 3. The results demonstrated excellent treatment efficiency for Cl^-, NO_3^- and SO_4^{2-}, achieving 99.5%, 99.98%, and 99.44%, respectively. All parameters meet QCVN 01-1:2018/BYT standards and are suitable for domestic use. These findings highlight the effectiveness of the water evaporator using light-absorbing membranes fabricated under natural drying conditions in converting seawater into fresh water.

Table 3. Results of anion analysis in seawater and harvested water

Parameters (mg/l)	Cl^-	NO_3^-	SO_4^{2-}	F^-
Input samples	17,470	2,986	2,357.5	0
Harvested samples	86.54	0.5	13.29	0.37
QCVN 01-1:2018/BYT	350	2	250	1.5

The results of cation of input water samples and harvested water samples using ICP-MS measurement are shown in Table 4. The concentrations of common metals (Na^+, K^+, Ca^{2+}, Mg^{2+} and heavy metals (in the harvested water samples meet the criteria of National Technical Regulation QCVN 01-1:2018/BYT on the domestic water quality. Especially, the treatment efficiency for Na^+, K^+, Ca^{2+}, Mg^{2+}achieving 99.87%, 85.2%, 94.34%, and 97.15% respectively. The findings confirm that heavy metal component in membrane did not affect harvested water quality.

Table 4. Results of canion analysis in seawater and harvested water

Specification/standards	Input samples	Harvested samples	QCVN 01-1:2018/BYT
Na^+ (ppm)	18,660	23.65	200
Ca^{2+} (ppm)	391.10	22.11	-
K^+ (ppm)	424.54	62.79	-
Mg^{2+} (ppm)	651.9	18.58	-
As (ppm)	N/D	N/D	0.01
Cd (ppm)	N/D	N/D	0.003
Pb (ppm)	N/D	N/D	0.01
Cr (ppm)	N/D	N/D	0.05
Cu (ppm	N/D	N/D	1
Sb (ppm)	0.008	N/D	0.02
Zn (ppm	0.193	0.023	2
Mn (ppm)	0.006	N/D	0.1
Ni (ppm)	0.001	N/D	0.07
Fe (ppm)	0.773	N/D	0.3
N/D (Not Detected)			

4. Conclusion

The process of manufacturing light-absorbing membranes from the sludge of a domestic wastewater treatment plant was optimized. Naturally dried membranes showed that the carbon material is evenly distributed on the cellulose membrane, reducing material accumulation and cracks compared to vacuum-dried membranes. The STS system using the TN_0.1 light-absorbing membrane achieved the highest evaporation rate of 2.65 $kg.m^{-2}.h^{-1}$ under 0.6 W irradiation conditions. Optimizing the manufacturing process not only reduces energy consumption but also enhances the evaporation rate of the device. The cation and anion levels in the harvested water samples all meet the QCVN 01-1:2018/BYT standards. The treatment efficiencies for Cl^-, NO_3^- and $SO_4{}^{2-}$ were 99.5%, 99.98%, and 99.44%, respectively.

References

[1] J. F. Inwald, W. B. D. Bruin, M. Yaggi, J. Árvai, Public Concern about Water Safety, Weather, and Climate: Insights from the World Risk Poll, Environmental Science Technology, Vol. 57, No. 5, 2023, pp. 2075-2083, https://doi.org/10.1021/acs.est.2c03964.

[2] C. He, Z. Liu, J. Wu, X. Pan, Z. Fang, J. Li, B. A. Bryan, Future Global Urban Water Scarcity and Potential Solutions, Nature Communications, Vol. 12, No. 1, 2021, pp 4667, https://doi.org/10.1038/s41467-021-25026-3.

[3] M. H. Yuan, S. L. Lo, Developing Indicators for the Monitoring of the Sustainability of Food, Energy, and Water, Renewable Sustainable Energy Reviews, Vol. 119, 2020, pp. 109565, https://doi.org/10.1016/j.rser.2019.109565.

[4] C. Chen, Y. Kuang, L. Hu, Challenges and Opportunities for Solar Evaporation, Joule, Vol. 3, No. 3, 2019, pp. 683-718, https://doi.org/10.1016/j.joule.2018.12.023.

[5] M. Gao, L. Zhu, C. K. Peh, G. W. Ho, Solar Absorber Material and System Designs for Photothermal Water Vaporization Towards Clean Water and Energy Production, Energy Environmental Science, Vol. 12, No. 3, 2019, pp. 841-864, https://doi.org/10.1039/C8EE01146J.

[6] L. Shi, X. Wang, Y. Hu, Y. He, Y. Yan, Solar-Thermal Conversion and Steam Generation: A Review, Applied Thermal Engineering, Vol. 179, 2020, pp. 115691, https://doi.org/10.1016/j.applthermaleng.2020.115691.

[7] Y. Li, T. Gao, Z. Yang, C. Chen, W. Luo, J. Song, E. Hitz, C. Jia, Y. Zhou, B. Liu, 3D-Printed, All-In-One Evaporator for High-Efficiency Solar Steam Generation Under 1 Sun Illumination, Advanced Materials, Vol. 29, No. 26, 2017, pp. 1700981, https://doi.org/10.1002/adma.201700981.

[8] Y. Zou, X. Chen, W. Guo, X. Liu, Y. Li, Flexible and Robust Polyaniline Composites for Highly Efficient and Durable Solar Desalination, Applied Energy Materials, Vol. 3, No. 3, 2020, pp. 2634-2642, https://doi.org/10.1021/acsaem.9b02341.

[9] C. Li, D. Jiang, B. Huo, M. Ding, C. Huang, D. Jia, H. Li, C.-Y. Liu, J. Liu, Scalable and Robust Bilayer Polymer Foams for Highly Efficient and Stable Solar Desalination, Nano Energy, Vol. 60, 2019, pp. 841-849, https://doi.org/10.1016/j.nanoen.2019.03.087.

[10] J. Zhu, X. Wang, J. Liang, X. Qiu, S. Chen, Y. Wang, Y. Wang, Broadband Solar-Driven Water Evaporator Based on Organic Hybrid Bandgap and Bio-Mimetic Interfaces, Ecomat, Vol. 5, No. 4, 2023, pp. e12323, https://doi.org/10.1002/eom2.12323

[11] L. Zhou, Y. Tan, D. Ji, B. Zhu, P. Zhang, J. Xu, Q. Gan, Z. Yu, J. Zhu, Self-Assembly of Highly Efficient, Broadband Plasmonic Absorbers for Solar Steam Generation, Science Advances, Vol. 2, No. 4, 2016, pp. e1501227, https://doi.org/10.1126/sciadv.1501227.

[12] P. Ying, M. Li, F. Yu, Y. Geng, L. Zhang, J. He, Y. Zheng, R. Chen, Band Gap Engineering in An Efficient Solar-Driven Interfacial Evaporation System, ACS Applied Materials Interfaces, Vol. 12, No. 29, 2020, pp. 32880-32887, https://doi.org/10.1021/acsami.0c09965

[13] B. Zhu, H. Kou, Z. Liu, Z. Wang, D. K. Macharia, M. Zhu, B. Wu, X. Liu, Z. Chen, Flexible and Washable CNT-Embedded PAN Nonwoven Fabrics for Solar-Enabled Evaporation and Desalination of Seawater, ACS Applied Materials Interfaces, Vol. 11, No. 38, 2019, pp. 35005-35014, https://doi.org/10.1021/acsami.9b12806.

[14] Y. Ren, R. Lian, Z. Liu, G. Zhang, W. Wang, D. Ding, M. Tian, Q. Zhang, CNT/Polyimide Fiber-Based 3D Photothermal Aerogel for High-Efficiency and Long-Lasting Seawater Desalination, Desalination, Vol. 535, 2022, pp. 115836, https://doi.org/10.1016/j.desal.2022.115836.

[15] J. Yan, W. Xiao, L. Chen, Z. Wu, J. Gao, H. Xue, Superhydrophilic Carbon Nanofiber Membrane with A Hierarchically Macro/Meso Porous Structure for High Performance Solar Steam Generators, Desalination, Vol. 516, 2021, pp. 115224, https://doi.org/10.1016/j.desal.2021.115224.

[16] D. V. Duong, C. H. Suk, Carbon-Based Sunlight Absorbers in Solar-Driven Steam Generation Devices, Global Challenges, Vol. 2, No. 2, 2018, pp. 1700094, https://doi.org/10.1002/gch2.201700094.

[17] D. T. H. Linh, N. D Binh, D. T. K. Phuong, P. T. Huyen, N. N. Duy, N. T. Hanh, T. N. Anh, P. H. Anh, N. M. Hoang, D. V. Duong, Evaluation of The Possibility of Applying Sewage Sludge as A Light Absorption Material in Solar-To-Steam Devices, TNU Journal of Science and Technology, Vol. 228, No. 14, 2023, pp. 170-176, https://doi.org/10.34238/tnu-jst.8802 (in Vietnamese).

[18] C. Chen, Y. Li, J. Song, Z. Yang, Y. Kuang, E. Hitz, C. Jia, A. Gong, F. Jiang, J. Zhu, Highly Flexible and Efficient Solar Steam Generation Device, Advanced Materials, Vol. 29, No. 30, 2017, pp. 1701756, https://doi.org/10.1002/adma.201701756.

[19] L. Yang, G. Chen, N. Zhang, Y. Xu, X. Xu, Sustainable Biochar-Based Solar Absorbers for High-Performance Solar-Driven Steam Generation and Water Purification, ACS Sustainable Chemistry Engineering, Vol. 7, No. 23, 2019, pp. 19311-19320, https://doi.org/10.1021/acssuschemeng.9b06169.

[20] X. Xu, Q. Chang, C. Xue, N. Li, H. Wang, J. Yang, S. Hu, A Carbonized Carbon Dot-Modified Starch Aerogel for Efficient Solar-Powered Water Evaporation, Journal of Materials Chemistry A, Vol. 10, No. 21, 2022, pp. 11712-11720, https://doi.org/10.1039/D2TA02302D.

[21] J. Hu, Y. Ge, X. Yao, K. Han, S. Xu, G. Bai, Bio-Derived Carbon-Based Materials with High Photothermal Conversion and Microstructure Transport Channels for Efficient Solar Evaporation and Water Treatment, Solar Energy Materials Solar Cells, Vol. 275, 2024, pp. 113028, https://doi.org/10.1016/j.solmat.2024.113028.