

THE INFLUENCE OF CHEMICAL ACTIVATORS ON ADSORPTIVE PROPERTIES AND SOLAR STILL PERFORMANCE OF ACTIVATED CARBON FROM CAESALPINIA SAPPAN WOOD

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Abstract

The availability of drinking water is a global concern today. A source of potable water is seawater processed using a distillation method utilising a solar still. Currently, seawater includes significant concentrations of heavy metals, including arsenic and lead, necessitating the absorption process. This study investigated the absorption of heavy metals from seawater with activated carbon derived from *Caesalpinia sappan* wood. The application of activators in the production of activated carbon influences both pore dimensions and the efficacy of the adsorption process. This investigation utilized 1 gram of ZnCl_2 , CaCl_2 , and Na_2CO_3 as activators. Activated carbon was introduced into the solar still to a depth of 1 cm. The properties of activated carbon were evaluated using Brunauer-Emmett-Teller (BET) and Scanning Electron Microscope (SEM) techniques. The salt test outcomes of the heavy metal absorption procedure were analyzed using XRF. The findings indicated that the activated carbon activated with ZnCl_2 exhibits superior pore properties and demonstrates the highest capacity for heavy metal absorption relative to other activators. The use of ZnCl_2 as an activator for activated carbon resulted in the maximum production ($3.5 \text{ L/m}^2/\text{day}$) and efficiency (58%) in solar stills by optimizing porosity, thermal conductivity, and interaction with marine salts. Furthermore, ZnCl_2 -activated carbon demonstrated an increased surface area and improved adsorption ability, significantly diminishing arsenic and lead levels. The parameters for the practical application of the results indicate that this technology is suitable for coastal and arid areas where saltwater desalination is crucial. This method can be applied in small-scale, off-grid water filtration systems, particularly in isolated populations with restricted access to potable water.

Keywords: solar still, activated carbon, *caesalpinia sappan* wood, adsorption, heavy metal.

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1. Introduction

One of the most disturbing and widespread problems in almost all developing nations and coastal communities is access to potable water supply [1]. Growing populations and changing climates contribute to the scarcity of fresh water and drive people into alternative sources of water. One of such plentiful but not very conventional sources is sea water but there is a long process to make it drinkable through desalination. The sea water has an abundance of salt and detrimental minerals and substances including heavy metals that not only are indigestible but can also cause health complications [2]. Thus, there is an urgent need for cost-effective and eco-friendly technology for the conversion of seawater into drinking water [3].

Dimensional analysis of water and its contaminants is a process which is also termed as advance boiling and hence is one of the potent methods for the removal of excess salts from the

seawater [4]. But this method was accompanied with some limitations, that are non-renewable energy sources such as all types of fossil fuels or electricity are utilized [5]. Solar stills use solar energy and are fairly economical. This is an advantage over the traditional methods [6]. These stills can eliminate salts from seawater quite efficiently, however they have their drawbacks and cannot effectively deal with heavy metals such lead, cadmium, copper and mercury – toxic elements that contain industrial waste [7]. According to The National Research and Innovation Agency Research in 2020, northern coastal parts of Java – like Semarang – have heavy metal concentrations that exceed the recommended limits specified by WHO. In some places, mercury (Hg) levels were recorded at over 0.5 µg/l, with lead (Pb) and copper (Cu) concentrations often exceeding 2 µg/l. These results demonstrate the scale of the problem that heavy metal pollution poses when lowering salinity of seawater.

Heavy metals in seawater is a huge problem for humanity. Heavy metals tend to bio accumulate resulting into chronic body pain due to kidney failure, neuro issues and even cancer [8]. For instance, Pb exposure is likely to impair the brain and developmental functioning in young all the way to adults. In old age severe lead deficiencies can cause osteoporosis or renal failure [9]. Low concentration of copper is required for optimal development in the human body. If not, this high concentration becomes toxic to the liver and lower digestive system [10]. Therefore, these metals need to be removed before the Saline water can be treated for lower contamination levels. This not only ensures efficiency but retains public sanitary measures.

There are some benefits of using solar still technology in the seawater desalination process [11]. This technology, in addition to being energy efficient, is also relatively simple to deploy in several places, including those which are off-the-grid [12]. However, the main challenge faced by solar still systems is their limitation in removing heavy metals [13]. In relation to this, the distillation process ought to remove most of the salts, while some heavy metals will remain either suspended in the distilled water, or not fully separated by means of the evaporation-condensation process [14]. In this sense, it is crucial to seek and develop other methods for enhancing the performance of solar stills towards removal of heavy metals [15]. One such method is the use of adsorbents such as activated carbon that can presumably adsorb heavy metals from seawater during the seawater slimes.

It should be emphasized that the very specific nature of activated carbon has enabled it to be classified as a material that can be used to treat water from pollution with heavy metals [16]. For these properties, the activated carbon has a very high surface area which allows it to have a great volume of pore structure for adsorption of various forms of particles including heavy metal ions [17]. The possibility of using activated carbon for water treatment processes has made filtration systems popular for the treatment of both domestic and industrial water [18]. As stated, activated carbon can be produced from a variety of organic feedstock including coal, coconut shell, and wood. In this research paper, there is something interesting about sappan wood or widely known as *Caesalpinia Sappan Wood* (CSW) as a source of activated carbon [19].

On the other hand, the manufacture of activated carbon has an activation stage which is expected to be a fundamental step in determining the adsorption capacity of the materials [20]. There are some activators that can be applied to increase the adsorption capacity of the charcoal such as zinc Chloride (ZnCl_2), Calcium Chloride (CaCl_2), and Sodium Bicarbonate (Na_2CO_3) [21]. That chemical activation can enhance the surface area of activated carbon up to 3500 m²/g [22]. Porosity, active surface area as well as pore volume of charcoal increase along with increasing of activation temperature [23]. The former engagement of solar still in the process of heavy metal adsorption made possible activated carbon with better chemical treatment to be prepared. Thus, some previous works reported that pigments from coconut shells and coal were based on activated carbon that adsorbs Cadmium (Cd) and Lead (Pb) ions without any traces [24]. It is detailed within this paper that, the layers of sappan wood are considered for examples, as materials such that other materials do not defeat the sun mirror system.

This research consists improving the solar still system by including a layer solar still with activated carbon in the system where seawater flows. Sun heats the seawater up and eventually causes it to evaporate, the activated carbon also plays as a special filter in that it is able to prevent heavy metals from contaminating the water when it vaporizes. This method is hoped to be able to absorb those kinds of heavy metals, which normally are not separated by normal distillation,

by the activated charcoal, thus upgrading the quality of the distilled water produced. Taking into consideration the implementation of activated carbon achieved from sappan wood biomass, a clear solution to the issue of water treatment can be found without much altering the economics and ecology of this technology. It is far easier to make activated carbon from sappan wood than it is from coal or other materials that cannot be replaced. And, the use of large quantities of sappan wood in Indonesia would promote local economic development, particularly in rural areas which are cut off from the advanced technology and energy sources. In any case, the work planned can contribute both towards the enhancement of solar still technology which is aimed at having a better efficacy in removing salts from seawater and heavy metals from water. The technology uses an activated carbon/coconut fiber composite prepared using sappan wood along with various other activators such as ZnCl_2 , CaCl_2 and Na_2CO_3 during the distillation process to remove heavy metals in order to clean seawater. It is not only an effective remedy for getting safe drinking water but also promotes eco-friendly practices which can be carried out in coastal and outlying regions. This research will also make way for others in utilizing other local sources or raw materials in developing activated carbon for water purification.

2. Experimental method

2. 1. Material preparation

The preparation of activated carbon involved using *Caesalpinia sappan* wood sourced from Ngawi Regency, East Java, Indonesia, which was cut, washed, and oven-dried before undergoing carbonization at 400°C for 8 hours to produce charcoal. **Fig. 1** describes the process of making activated carbon. **Fig. 1, a** is charcoal from secang wood that has not been activated, **Fig. 1, b** is the process of mixing secang wood charcoal with several activators and covered with aluminum foil, **Fig. 1, c** is activated wood charcoal. The resulting charcoal was sieved to a 40-mesh size and chemically activated using CaCl_2 , Na_2CO_3 , and ZnCl_2 1 gram, followed by heating at 400°C for 3 hours under a nitrogen atmosphere. Concurrently, seawater samples were collected from the northern coast of Lamongan, East Java, Indonesia, and stored in sterilized glass containers under dark and cool conditions. The salinity of the seawater was adjusted to 20%, and heavy metal contaminants, including PbNO_3 , FeCl_3 , and $\text{Mn}(\text{NO}_3)_2$ (0.1 N, 5 mL each), were introduced under continuous stirring to simulate pollution. These preparations ensured a standardized setup for evaluating the adsorption efficiency of the activated carbon under controlled, realistic conditions.

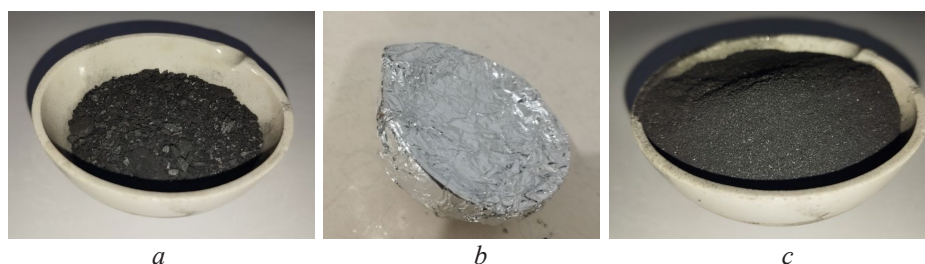


Fig. 1. Preparation of activated carbon: *a* – sappan wood charcoal; *b* – activator solution mixing process; *c* – sappan wood activated charcoal

2. 2. Experimental unit

The research was conducted at the Solar Energy and Alternative Energy Laboratory, Department of Mechanical Engineering, Widyagama University, in Malang, East Java, Indonesia. The geographical condition of the city of Malang is characterized by a latitude of -7.266667 and a longitude of 112.716667 , or with coordinates $7^\circ 16'$ South Latitude and $112^\circ 43'$ East Longitude.

The cover and walls of the double-slope solar still are made of 3 mm thick clear glass, while the bottom is made of 5 mm thick glass. To minimize heat and steam loss, all glass is sealed with silicone adhesive. Equipment setup can be seen in **Fig. 2**. Activated carbon is placed in a solar still with a height of 1 cm as shown in **Fig. 3**.



Fig. 2. Multi stage solar still

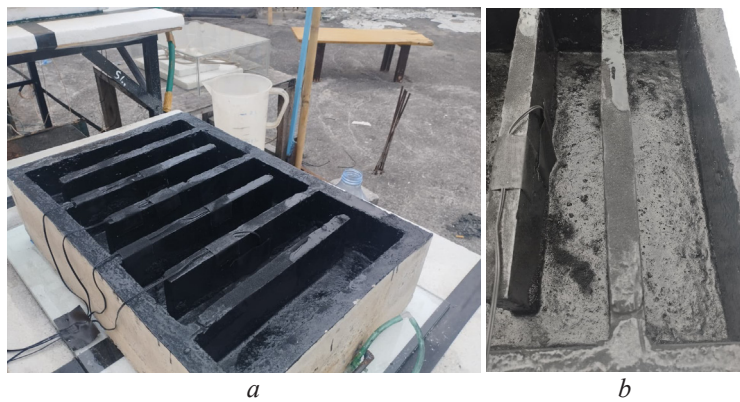


Fig. 3. Activated carbon on the absorber plate of the solar still fins: *a* – solar still absorber plate; *b* – activated carbon on solar still absorber plate

2. 3. Measuring equipment

Various instruments for measuring parameters used are thermocouples, pyranometers, anemometers, and measuring cups. The associated error percentage, accuracy, and range of instruments can be seen in **Table 1**.

Table 1
Measuring equipment

No.	Instrument	Accuracy		Range		% Error
		Min	Max	Min	Max	
1	Thermocouple	−0.1°C	0.1°C	−100°C	200°C	0.25%
2	Pyranometer	−1.0 W/m ²	1.0 W/m ²	0 W/m ²	1200 W/m ²	1%
3	Anemometer	−0.1 m/s	0.1 m/s	0 m/s	25 m/s	5%
4	Measuring cup	−1.0 mL	1.0 mL	0 mL	200 mL	1%

2. 4. Experimental procedure

The research was conducted experimentally, focusing on testing a double-slope solar still (SSDS) using seawater with added contaminants. Activated carbon poured into the solar still is Activated Carbon Caesalpinia Sappan Wood with activator ZnCl₂ 1 g (ACCSW ZnCl₂ 1 g), Activated Carbon Caesalpinia Sappan Wood with activator CaCl₂ 1 g (ACCSW CaCl₂ 1 g) and Activated Carbon Caesalpinia Sappan Wood with activator Na₂CO₃ 1 g (ACCSW Na₂CO₃ 1 g) until the height of activated carbon is 1 cm. Each activated carbon variation was placed in a different solar still. The SSDS was equipped with a cover glass tilted towards the east and west to optimize

solar radiation absorption. The water height in SSDS was maintained at 10 mm, and cooling water with a flow rate of 1.1×10^{-4} liters per second was added during the test. Activated carbon was added to the absorber plate of the SSDS to filter seawater with contaminants and enhance the distillation process. Data on temperature, solar radiation intensity, wind speed, distillate output, and the reduction of contaminants were measured every 5 minutes from 7 a.m. to 5 p.m. The study aimed to produce desalinated water while reducing contaminants through filtration and solar distillation.

3. Result and discussion

3. 1. Surface characteristic

Table 2 illustrates the pore size distribution for each activator, thereby confirming the interdependence between raw constitution and chemical activation. Untreated in the form of powder, secang wood has the lowest pore size of all the materials considered in this study. This is consistent with the basic structure of its natural constituents such as: cellulose, hemicellulose, lignin and the center of the green wood which is enriched with the active component i.e. brazilin $C_{16}H_{14}O_5$ [25]. These ingredients lead to a denser, tighter microstructure which restricts pore development.

Table 2

Specific surface area, pore volume and pore size of the adsorbents

Adsorbents	BET surface area (m^2/g)	BJH pore volume (cm^3/g)	BJH pore size (nm)
ACCSW $ZnCl_2$ 1 g	6.6521	0.9158	5.5432
ACCSW $CaCl_2$ 1 g	7.4697	0.9752	5.9046
ACCSW Na_2CO_3 1 g	4.3651	0.5564	4.4323
CCSW	3.6396	0.4369	4.0758
Caesalpinia Sappan Wood (CSW)	3.4532	0.8371	3.5268

Being non chemically activated, secang wood on the other hand, has no such expansive processes, thus maintaining its original compact structure. However, activator such as $ZnCl_2$, $CaCl_2$, and Na_2CO_3 alter the natural polymeric interlinks of the carbon-based material, leading to higher pore development and increased surface area. For example, $ZnCl_2$ alters the structure of lignin and hemicellulose leading to the formation of extra micropores and mesopores. Likewise, the activation of $CaCl_2$ and Na_2CO_3 expands thermal decomposition and etching during activation, further increasing the pore size.

On the other hand, due to the absence of these activators in secang wood, it continues to sustain its hard structure, as given the case where cellulose fibrils are preserved and lignin encases it. In addition, one cannot discount the function of brazilin in strengthening the structure internally. The said compound enhances the tree's morphology and avoids the formation of voids space which may result in like an enlargement of pore dimensions [26]. Therefore, secang wood serves as a baseline to show the extent of the changes brought about by chemical activators on the pore morphology. This discussion highlights the importance of activation especially in determining the pore volume, pore size and surface area for the required application in adsorption [27].

Zinc chloride ($ZnCl_2$) however, upon treatment with activated carbon, acts as a Lewis acid catalyst, which delivers hydration, aromatization and pores within the carbon structure. It is clear that, by heating zinc chloride in the presence of activated carbon, the zinc placed on the activated disperses as hydroxyl ($-OH$) on the surface of carbon coupled with heating that yields water (H_2O) and a combination of chloride ($C-Cl$) [28]. This causes the elimination of volatiles in the carbon matrix. In addition, $ZnCl_2$ speeds up aliphatic turned chloric ones having higher thermal stability than aromatic ones. This process results in the formation of micro pores, thus the area of activated carbon rises, enabling it to hold small molecules. Calcium chloride ($CaCl_2$) acts as a dehydration and pore-forming agent especially for the mesopore formation. Upon mixing with activated carbon, $CaCl_2$ decomposes into calcium oxide when the carbon containing hydroxyl and carboxyl ($-COOH$) groups is heated, producing hydrogen chloride gas (HCl) in the process [29]. Sodium carbonate (Na_2CO_3) is a basic precursor which helps in the synthesis by eliminating the

acidic functional groups on the carbon surface and also evolves gases on heating [30]. Na_2CO_3 can interact with carboxyl ($-\text{COOH}$) groups to generate sodium carboxylate salts, water (H_2O) and carbon dioxide (CO_2) [31]. The resultant CO_2 together with water vapor build up gas pressure in the porous carbon structure preventing collapse of the pores and formation of more pores. Also, CO_2 could interact further with the intact carbon framework to yield carbon monoxide (CO) [32], which also improves pore formation. Such porous activated carbon materials with broader structures should be better suited for the adsorption of larger macromolecules.

From Fig. 4 the isotherm graphs presented in this figure indicate that the material is a mesoporous adsorbent with a pore size of 2 to 50 nm which can be classified as Type IV isotherm [33]. Generally, this kind of isotherm possesses a slight upward slope at lower relative pressures as a result of monolayer-multilayer adsorption but then a steep slope at higher pressures which indicates capillary condensation of mesopores [34]. Activation of the chemical nature retains almost Intact structure of secang wood that belongs to a wood of small and poorly developed pores. It has therefore limited adsorption capacity towards gases or other substances as reflected in the low isotherm curve.

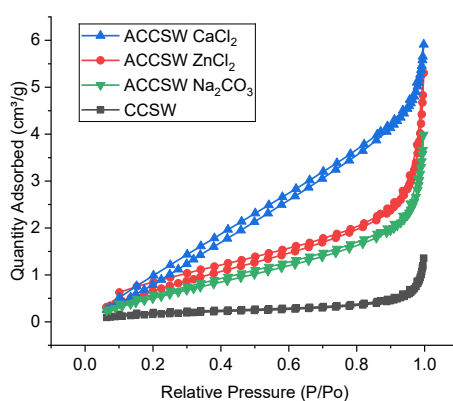


Fig. 4. N_2 adsorption-desorption isotherms curves

The ACSW treated with Na_2CO_3 has an adsorption ability that is greater than that of untreated ACSW, but lower than that for CaCl_2 and ZnCl_2 , so it has an intermediate level of adsorbency. The curve depicts a progression that indicates pressure has an impact on adsorption but is less abrasive than expected. There is evidence linking the use of Na_2CO_3 to the expansion of pores during the activation portion of the experiment due to the production of gas in the form of CO_2 and water. It is only natural then, that the use of Na_2CO_3 resulted in an overall more diverse pore distribution as the mesopores and bigger size pores were accumulated. It is attributed to the fact that the amount of micropores that were generated was comparatively low in relation to the amount of mesopores than were generated by using both ZnCl_2 and CaCl_2 [35], which resulted in a more moderate adsorption property. The ZnCl_2 modified ACSW remains less than the calcium modified, however, the two are higher than the unmodified ASN and the Na_2CO_3 version. It was noted that as the relative pressure grew larger, so did the amount adsorbed. The use of ZnCl_2 active carbon enables the transformation from the carbon matrix into benzene, which in turn generates micropores [36]. Nonetheless, this guarantees that the volume is subsequently low on higher pressures because they were dominated by micropores, thus making the adsorbing surface for lower volume molecules more expansive. It demonstrates balance and favor in the development of mesopores and micropores, resulting in the ZnCl_2 modified version ideal for retaining small molecules. A marked progression of mesopores and macropores are noted which in turn enabled the use of more Na_2CO_3 enabling the greatest saturation across all the previously mentioned substances, especially in relation to the saturation at high pressures. This indicates a significant development of mesopores and macropores. Through its interaction with hydroxyl and carboxylic groups, CaCl_2 aids in the partial gasification and pore development. This develops mesopores which enhances the adsorption capacity at higher relative pressures. The isotherm implies that the carbon modified with CaCl_2 is most suitable for adsorption of large molecules which need higher surface area and volume of pores.

3. 2. SEM-EDX analysis of activated carbon before adsorption heavy metal

Fig. 5 SEM presents the change of the microstructure of sappan wood as seen from the activated carbon processes of carbonization and chemical activation. The structure of the raw wood of sappan has a mesquite appearance, being slightly consolidated with cellulose and hemicellulose lignin. The three lignin, cellulose and hemicellulose tempered the wood and made it more stronger but on the other side at this point pores did not have any appreciable volume with most were being less than 2 nm in size, hence did not have a significant adsorptive capacity. The wood structure's change during carbonization is perhaps the most substantial alteration in the wood's nature. Carbonization is achieved through heating of the substance at elevated temperatures while excluding oxygen in order to carbonize it [37]. During this process, volatile substances that include water, hemicellulose, and some portions of lignin are lost. The carbon skeleton that is formed has pores but not enlarged ones [38]. It is defined by the micropores even though the material's surface area is quite restricted, predominantly comprising pores with a diameter of less than 2 nm. This stage is crucial in the development of activated carbon which is further supplemented through chemical activation [39].

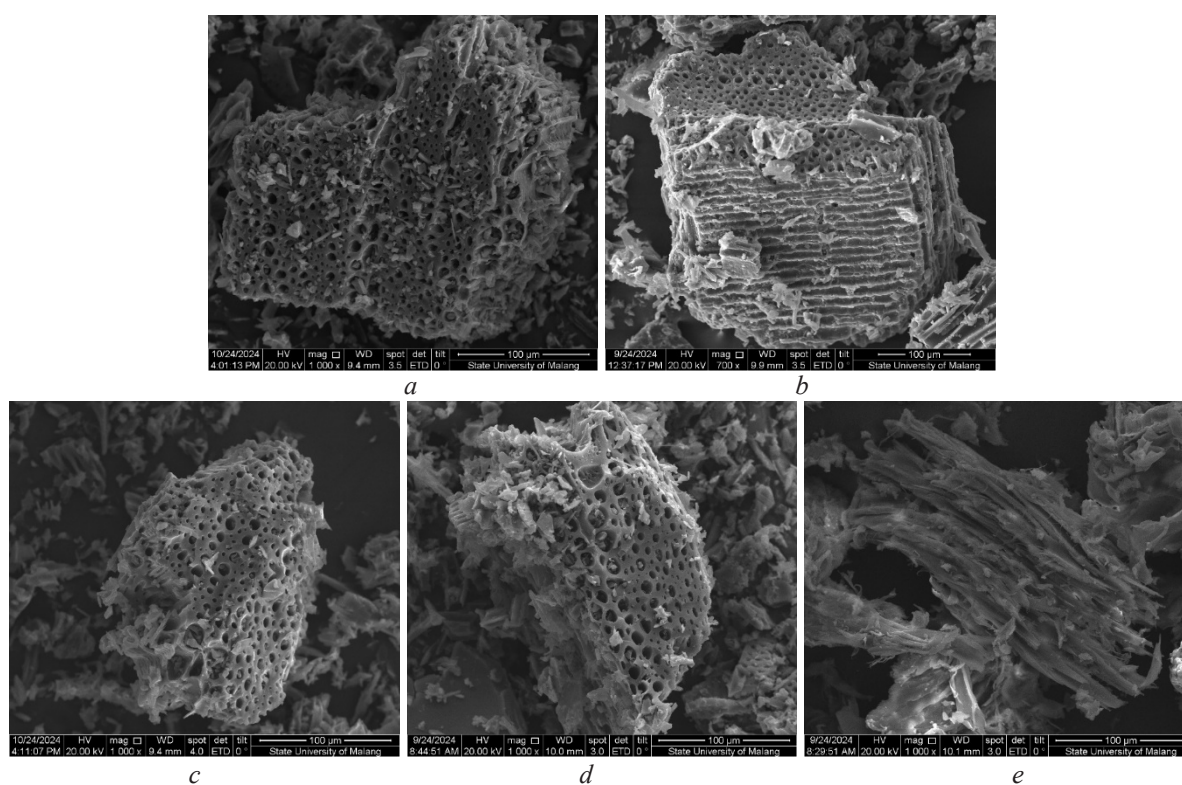


Fig. 5. SEM of activated carbon before seawater absorption: *a* – activated carbon caesalpinia sappan wood with activator ZnCl_2 ; *b* – activated carbon caesalpinia sappan wood with activator CaCl_2 ; *c* – activated carbon caesalpinia sappan wood with activator Na_2CO_3 ; *d* – carbon caesalpinia sappan wood; *e* – caesalpinia sappan wood

ZnCl_2 makes the structure of the material more complex because there is a high amount of micropores and a low amount of mesopores [40]. ZnCl_2 dehydrates thus leading to breakdown of lignin and cellulose and formation of new pores. This activation leads to a great increase in the specific surface area of the material, reaching values in the range of 700–1500 m^2/g , primarily depending on the conditions of the process. The activated carbon that is produced from this type of activation would be expected to be adsorbing small heavy metals or toxic gases because of its high volume of pores with diameters less than 2 nm. On the other hand, when CaCl_2 was used, the material exhibited a greater uniformity in the distribution of the pores, most mesopores of 2–50 nm in diameter predominated. In this process. That compound then decomposes to form a more even pore structure. This activation also increases the strength of the material making it appropriate for

usage in physical filters or adsorption of large organic compounds. The range of specific surface area for materials activated in CaCl_2 solution varies from 500–1200 m^2/g . In contrast, activation using Na_2CO_3 results in the formation of materials with broader pore size ranging from mesopores to macropores (> 50 nm in diameter). In the advanced carbonization, Na_2CO_3 acts as one of the catalysts which resulted in a more developed and wider pore structure. This material is applicable for large molecules adsorption such as organic pollutants in water exhibits a specific surface area of about 400–900 m^2/g . The presence of these large pore makes Na_2CO_3 activated carbon quite effective in liquid and water treatment.

SEM micrographs with various activating agents depict that each of the methods applied has a different influence on the pore architecture and surface area of the material [41]. Nanoparticles of ZnCl_2 led to attainment of smallest pores that are said to be ideal for the adsorption of small-sized molecules, whereas, CaCl_2 and Na_2CO_3 formed larger pores that were ideal for molecules of medium to large sizes [30]. Such carbonization and chemical activation processes help in enhancing the surface area of the material, while reshaping its properties to suit application requirements such as gas processes, removal of pollutants from water and large filtration [42]. These transformations illustrate the importance of choosing an activation agent that corresponds to the expected end use of the material in question.

Table 3 shows the EDX analysis of activated carbon before absorption. In every sample, it seems carbon is the leading constituent with the ACCSW samples containing the highest amounts especially the ones treated with ZnCl_2 and Na_2CO_3 . In all samples, oxygen appears to be the second most prevalent element, albeit its percentage is range in different samples [43]. The ranges reflect the extent of the oxidation and the amount of oxygen containing functional groups that decorates the surface of the carbon. Among the samples, CSW, which is the control, contains the highest amount of oxygen and the lowest quantity of carbon in relation to the chemically activated ACCSW samples [44]. This may imply that the structural arrangement of carbon is less sophisticated with a greater quantity of oxygenated functional groups and perhaps this is due to the low amounts of chemical activation [32].

The chemical addend used during activation determines the presence of various trace elements such as ZnCl_2 , CaCl_2 , Na_2CO_3 . Zinc for example, is noted to be present only in the ACCSW sample that was treated with ZnCl_2 , indicating its uptake by the material during activation. Likewise, calcium and chlorine are introduced through CaCl_2 but in small yet detectable amounts suggesting that they assist in changing the carbon structure of the material. Sodium on the other hand only registered in the ACCSW sample for Na_2CO_3 , which indicates specialized incorporation of the element into the material. Some sample materials do not contain these elements because they were added through specific additives rather than the carbon source.

Table 3

EDX analysis of activated carbon before absorption

ACCSW ZnCl_2 1 g			ACCSW CaCl_2 1 g			ACCSW Na_2CO_3 1 g			ACCSW			CSW		
Ele- ment	Wt %	Atomic %	Ele- ment	Wt %	Atomic %	Ele- ment	Wt %	Atomic %	Ele- ment	Wt %	Atomic %	Ele- ment	Wt %	Atomic %
C	83.9	84.4	C	84	88	C	85.1	88.7	C	86.5	89.6	C	63.6	70
O	14	13.6	O	14.9	11.7	O	13.9	10.9	O	13.2	10.2	O	36.2	29.9
Cl	1	1	Cl	0.5	0.2	Na	0.5	0.3	Ca	0.4	0.1	Ca	0.2	0.1
Ca	0.2	0.1	Ca	0.6	0.2	Ca	0.5	0.1	Na	0	0	Na	0	0
Zn	0.9	0.9	Zn	0	0	Zn	0	0	Zn	0	0	Zn	0	0

3. 3. SEM-EDX analysis of activated carbon after adsorption heavy metal

The relationship of heavy metals to activated carbon, modified with cementing agents such as ZnCl_2 , Na_2CO_3 , and CaCl_2 , is determined in **Fig. 6** by the unique characteristics of the carbon surface created by each activator. This alters the internal structure, chemistry, and functional groups of the AC, which govern its adsorption capacity and mechanism for heavy metals.

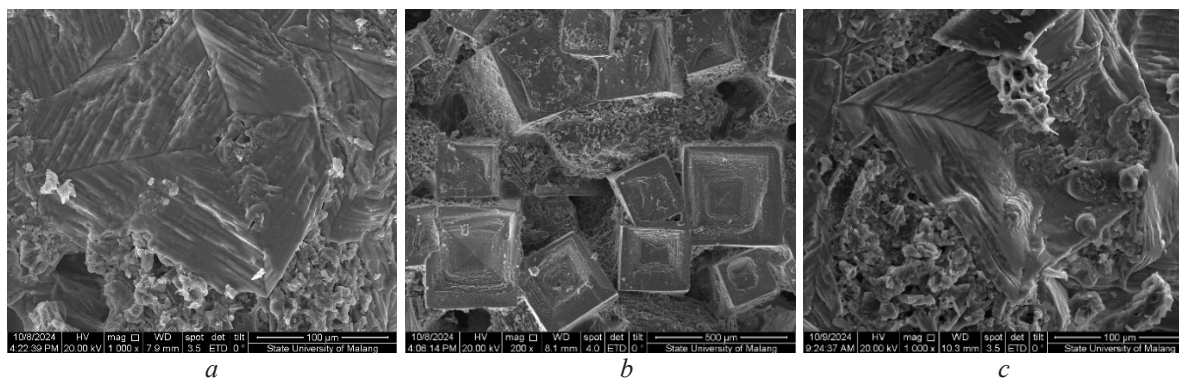


Fig. 6. SEM analysis of activated carbon caesalpinia sappan wood: *a* – activator ZnCl_2 ; *b* – activator Na_2CO_3 ; *c* – activator CaCl_2 after adsorption heavy metal in seawater

Due to the extensive micro- and meso-pores in such materials, ZnCl_2 -Activated Carbon is very porous. The introduction of ZnCl_2 to the compound prevents the pyrolyzed material's volatile parts from penetrating the high surface area. This porosity boost maximizes the possibilities of physical absorption whereby heavy metal ions settle on the surface via Van der Waals bonding and electrostatic interaction [45]. The addition of ZnCl_2 increases the amount of oxygen functional groups on the surface such as carbonyl and carboxyl groups that enhance complexation of metal ions on the surface. For heavy metals such as Mercury (Hg^{2+}) and Arsenic (As^{3+}) ions, ZnCl_2 -activated carbon is highly efficient because it has a large number of adsorption centers and can effectively block these ions in its cavelike structure [46].

ACCSW CaCl_2 approaches the construction of the AC surface layer by modifying strategy chemisorption kinetic by increasing the number of its reactive sites [47]. During the modification process, the carbon matrix was engaged by calcium ions and, afterwards, calcium-based compounds, for instance, calcium oxide or hydroxide, may form on the surface. These compounds assist the precipitation or ionic binding of certain heavy metals, e.g. lead, Pb^{2+} and cadmium, Cd^{2+} [48]. Calcium modified sites which interact with the heavy metals complexes are very stable and result in strong chemical bonding. CaCl_2 treated carbon SEM images show irregular structures and crystallite morphology dominant which indicates the presence of these reactive compounds. Although the pore structure generated by CaCl_2 activation may be smaller than that from ZnCl_2 activation, the chemically active sites are highly useful for metals which have strong ionic or covalent attachments. ACCSW Na_2CO_3 SEM images show that the Na_2CO_3 treated carbon has a layered and fibrous structure that is suitable for ion exchange and promotes the adsorption of positively charged metal ions. Moreover, it has been noted that sodium carbonate can also be used to establish alkaline conditions, which can help in the precipitation of nickel (Ni^{2+}) and chromium (Cr^{3+}) in a hydroxide form [49].

Everything considered, of the three – ZnCl_2 being the best overall in physical adsorption because of high surface area, whereas CaCl_2 and Na_2CO_3 could be used where chemical interaction and ion exchange are preferred respectively. So, based on the heavy metal type and interaction mechanisms the choice of activator can be made.

Table 4 shows the EDX analysis activated carbon after absorption ACCSW ZnCl_2 exhibits high chlorine (21.5% wt, 9.9% Atomic) and oxygen (10% wt, 10.7% Atomic) contents, suggesting the presence of chlorinated and oxygenated functional groups. These groups, such as hydroxyl ($-\text{OH}$) and carboxyl ($-\text{COOH}$), enhance the material's polarity and promote surface complexation with heavy metal ions [50]. Additionally, ZnCl_2 creates a highly porous structure with increased micro- and mesopores, facilitating the physical adsorption of smaller heavy metal ions like arsenic (As^{3+}) or mercury (Hg^{2+}) [51]. Chlorine residues may also interact with cationic heavy metals through ion-exchange mechanisms, improving adsorption efficiency [52]. ACCSW CaCl_2 demonstrates higher carbon content (58.5% wt, 74.5% Atomic) but reduced oxygen and chlorine levels compared to ACCSW ZnCl_2 . Calcium-modified sites likely form during activation, introducing basic functional groups such as calcium oxides or hydroxides, which chemically bind heavy metal ions. Chemisorption dominates in this case, with lead (Pb^{2+}) and cadmium (Cd^{2+}) forming stable

precipitates or ionic bonds with the calcium-rich surface. The crystalline morphology also supports selective adsorption, targeting metals with strong affinities for calcium compounds [53]. ACCSW Na_2CO_3 enhances surface basicity through carbonate ($-\text{CO}_3^{2-}$) and hydroxyl groups, as evidenced by its moderate oxygen content (8.2% wt, 7.8% Atomic) and high sodium levels (15% Wt, 9.8% Atomic). These basic sites favor ion exchange, particularly for divalent cations like copper (Cu^{2+}) and nickel (Ni^{2+}). The layered morphology increases accessibility for ion-exchange reactions, while sodium carbonate alkalinity promotes the precipitation of metals as hydroxides [54].

Table 4

EDX Analysis of activated carbon after absorption

Element	ACCSW ZnCl_2 1 g		ACCSW CaCl_2 1 g		ACCSW Na_2CO_3 1 g	
	wt %	Atomic %	wt %	Atomic %	wt %	Atomic %
C	49	66.8	58.5	74.5	58.9	74.5
O	10	10.7	7.8	7.4	8.2	7.8
Na	17.3	11.4	14.7	9.8	15	9.8
Mg	0.9	0.8	0.7	0.5	0.6	0.4
Cl	21.5	9.9	18.1	7.7	17	7.3
Ca	0.7	0.3	0.3	0.1	0.4	0.2
Zn	0.6	0.1	0	0	0	0

3. 4. X-ray fluorescence analysis

Table 5 shows the XRF analysis of seawater and salt after absorption with activated carbon. The produced salt is shown to be efficient in removing heavy metals like chromium (Cr), nickel (Ni), copper (Cu), and lead (Pb) and zinc-based active sites are the reason for this through adsorption. The surface area increased due to the introduction of active zinc oxide (ZnO) or hydroxide ($\text{Zn}(\text{OH})_2$) with the high content (1.73%) of zinc from ZnCl_2 as a result, the zinc oxide or hydroxide strongly adsorb with the metals entails arsenic (As) and lead (Pb), and the intensity relies on the extent of surface complexation. Furthermore, the high content of chlorine (80.1%) and zinc are positive factors with regard to the ability of this salt to contribute to ion exchange and chemical binding of heavy metal ions [52]. This salt displays moderate adsorption of arsenic (0.05%) and lead (1.1%) but has lower efficiency in the adsorption of nickel (0.02%) and copper (0.04%) due to its functional limitation in carbonate or hydroxide group. Salt from ACCSW Na_2CO_3 however exhibits strong ion exchange and precipitation properties due to its enhanced carbonate appearance. This salt keeps high percentage of chlorine 83.29 and calcium at 1.95 and adds ($-\text{CO}_3^{2-}$) and ($-\text{OH}$) that constitute basic carbonates and weak bases which favor the precipitation of metal carbonates and hydroxides. It follows therefore that Na_2CO_3 advocates for enhanced degradation of metals because it is not only more basic than ZnCl_2 but also assists in the degradation of heavy metals other than the use of ion exchange such as nickel (0.027%) and copper (0.065%). Still, the above-mentioned cations did not work alone since arsenic (0.095%) and also microamounts of Pb (1.5%) were effectively bound through precipitation wherein again the reduced zinc content (0.09%) increased the availability of metals that were more dominant and were inclined towards the adsorption sites of zinc.

Table 5

XRF analysis of seawater and salt after absorption with activated carbon

Salt compound (%)	Mg	S	Cl	K	Ca	Cr	Fe	Ni	Cu	Zn	As	Br	Nd	Pb
Sea water	0	3.2	87.5	2.2	3.29	0.12	0.2	0.01	0.18	0	0	1.2	0	2.1
ACCSW ZnCl_2	8	3.8	80.1	2.22	1.4	0.04	0.05	0.02	0.04	1.73	0.05	1.12	0.33	1.1
ACCSW Na_2CO_3	5.1	4.06	83.29	2.59	1.95	0	0.091	0.027	0.065	0.09	0.095	0.702	0.44	1.5
ACCSW CaCl_2	7	4.48	81.5	2.637	1.1	0	0.042	0	0.055	0.12	0.18	0.986	0.41	1.49

Forming salt that were filtered with ACCS CaCl_2 demonstrates a powerful ability to eliminate dangerous heavy metals such as lead and arsenic because of the presence of calcium which has chemisorptive properties. With low amounts of calcium (1.1%) alongside high amounts of chlorine (80.5%), calcium tends to combine with other elements and form strong complexes that include calcium arsenate and lead-calcium. This salt absorbs the greatest amounts of lead (2.49%) and arsenic (0.18%) and therefore it is an excellent sorbent for these metals. On the other hand, CaCl_2 activator does not exhibit strong adsorption towards nickel (0%) and copper (0.055%) due to having a low ion exchange capacity [55].

3. 5. Solar still performance with various activator activated carbon

A five-day testing of the solar stills' performance using activated carbon derived from *Caesalpinia sappan* wood (ACCSW) treated with the chemicals ZnCl_2 , CaCl_2 and Na_2CO_3 , was conducted to determine the output capacity and efficacy shown in Fig. 7. The activators were measured for effectiveness in relation to solar insolation for improvement of the evaporation condensation cycle and the seawater components of the chemical treatment. the observed relationships between productivity and efficiency confirmed the essentiality of the changes in the chemical and structural modifications of each particular activator to the solar still performance.

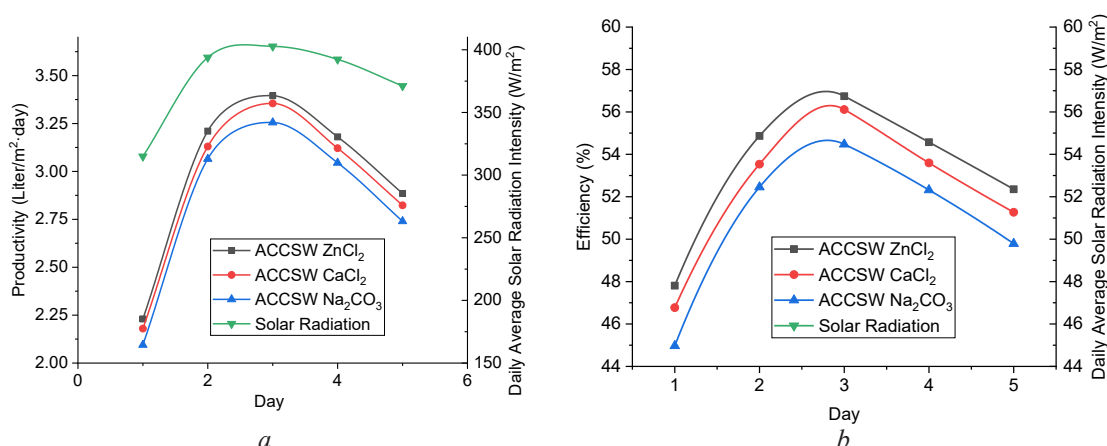


Fig. 7. Solar still: *a* – productivity; *b* – efficiency performance with various activator activated carbon

In terms of productivity, ACCSW ZnCl_2 was the most productive reaching a 3.4 l per m^2 of daily output on the 3rd day. ZnCl_2 carbon framework structure with a very high porosity thus allowing for sufficient water retention, increased thermal exchange as well as greater evaporation surface area. With this, once solar energy is intensified the porous form of the structure allows the thermal energy to be effective in the evaporation phase. On the other hand, ACCSW CaCl_2 had a slightly lesser productivity which was approximately 3.36 l per m^2 of the surface in the second day. The calcium-based compounds added during activation enhance the thermal activity on the carbon surface towards the end of the evaporation cycle but without the great porosity as in the case of ZnCl_2 . Conversely, ACCSW treated with Na_2CO_3 has the lowest output, slightly below 3.26 l per m^2 per day. This is due to the high degree of porosity and thermal conductivity of Na_2CO_3 treated carbon that limits its efficiency of absorbing solar radiation for generation of water vapor.

The data on efficiency level and productivity level were positively correlated with a regression coefficient of 4.674, because the ACCSW treated with ZnCl_2 had reached an efficiency level of 56.74 percent on the third day. There are functional groups such as zinc oxide (ZnO) and hydroxide ($\text{Zn}(\text{OH})_2$) which are formed by the addition of ZnCl_2 , and these groups interact with the elements in seawater to enhance the salts and other impurities adsorption as well as assist the electrolyte in evaporating water [56]. The ZnCl_2 carbon interact with the contained carboxyl groups and nucleophilic groups with the increased chlorinated carbon particles, which increase the thermal composites and boost the chemical activity of the particles thus allowing for effective solar

energy conversion [57]. On the other hand, the maximum efficiency of about 56,11 percent was recorded for the ACCSW that was treated with CaCl_2 . CaCl_2 along with calcium oxide additives which were derived from the calcium compounds on the carbon surfaces reacting with the seawater salt deposits helps to remove many other impurities but reduces their thermal efficiency especially in comparison to ZnCl_2 treatment. The utilization of Na_2CO_3 when treating the ACCSW resulted in the least efficacious outcome registering a peak of nearly 54.47 percent. Increased basicity is created using the CO_3^{2-} ions, permitting the basicity to react with the dissolved salts in seawater to produce sodium chloride and magnesium carbonate precipitates [58].

The chemical interrelations explain to a reasonable level the role of activators and seawater. The interaction of carbon which had been treated with ZnCl_2 with seawater ions leads to the formation zinc compounds which adsorb the salts and heavy metals [13]. ZnCl_2 interacts with magnesium and calcium ions existing in seawater, resulting in the precipitation of magnesium chloride and calcium chloride, which are later disposed of during the distillation process [59]. These other compounds are responsible in enhancing the purity of the water describing the higher productivity and efficiency values of ZnCl_2 which is above all others. Similarly, the water quality is improved through calcium carbonate and calcium sulfate which precipitate from the mix of seawater with CaCl_2 [60]. Similar to other compounds, Na_2CO_3 is capable of reacting with seawater in an ion exchange and precipitation reaction resulting in the formation of sodium chloride and magnesium carbonate. These compounds assist in the removal of contaminants and impurities but are predicted to impair the overall thermal adsorption and properties of the carbon [30].

3. 6. Research limitations and future directions

This research focused on the characterization and performance of activated carbon derived from *Caesalpinia sappan* wood (ACCSW) activated with ZnCl_2 , CaCl_2 , and Na_2CO_3 , where ZnCl_2 -treated ACCSW exhibited the highest adsorption capacity for heavy metals and the best solar still performance. The experiments were conducted in an open outdoor environment under direct solar radiation using a multi-stage solar still apparatus. The salinity of seawater in the system was fixed to ensure data consistency, while environmental parameters such as humidity, wind velocity, and solar radiation intensity naturally followed ambient conditions without laboratory control. This realistic setup enhanced the representativeness of field performance but may also introduce variability due to weather fluctuations. Among the heavy metals observed, As^{3+} , Hg^{2+} , and Pb^{2+} were the most dominantly adsorbed species, reflecting strong chemical affinity with the activated carbon surface functional groups.

Although the results demonstrate clear differences in adsorption capacity and water-distillation efficiency, several limitations should be considered when interpreting the applicability and reproducibility of the findings.

First, the experiments were performed under open outdoor conditions, where solar radiation, humidity, and ambient temperature were not strictly controlled. This realistic setting increases representativeness under field operation but limits precise reproducibility, since short-term weather fluctuations can affect thermal gradients, distillate yield, and adsorption kinetics. Reproducing the results therefore requires similar climatic conditions and solar intensities.

Second, the seawater feed used for testing had a fixed salinity and controlled composition, which does not reflect the ionic and organic complexity of natural seawater or wastewater. Consequently, the results are most applicable to systems of comparable salinity and contaminant levels; applying the findings to different water sources may require calibration of adsorption parameters.

Third, the activation and testing were conducted on a batch scale and within limited operating hours. The scalability, mechanical stability, and regeneration efficiency of ACCSW during repeated cycles were not verified. Reproducibility in larger-scale or continuous systems will depend on maintaining comparable activation ratios, heating profiles, and chemical concentrations used in this work.

Fourth, the environmental and economic aspects of the activation process particularly the fate of residual Zn and salt effluents were not evaluated. Therefore, before industrial application, environmental impact assessments and cost analyses are essential to ensure sustainable deployment.

Further research needs to explore the scalability and reproducibility of the activation process through continuous or semi-continuous systems, as well as field-scale trials to validate stability, cost efficiency, and regeneration performance. Further improvements could involve integrating ACCSW into hybrid solar stills or combining it with photocatalytic adsorption mechanisms to enhance both distillation yields and contaminant removal efficiency. In addition, conducting long-term monitoring and technological-economic analysis will help evaluate the sustainability and practical application of *Caesalpinia sappan*-based activated carbon in decentralized desalination and water filtration for coastal areas.

4. Conclusions

The choice of activator significantly influences the pore size, surface area, and overall adsorptive capacity of the activated carbon. ZnCl_2 -treated ACCSW exhibited a balanced development of micropores and mesopores, with a specific BET surface area of $6.6521 \text{ m}^2/\text{g}$, making it ideal for adsorbing small molecules and heavy metals like arsenic (As^{3+}) and mercury (Hg^{2+}). CaCl_2 -treated ACCSW had the highest pore volume ($0.9752 \text{ cm}^3/\text{g}$) and pore size (5.9046 nm), favoring adsorption of larger molecules like lead (Pb^{2+}). Na_2CO_3 -treated ACCSW, with moderate porosity and a BET surface area of $4.3651 \text{ m}^2/\text{g}$, showed broader adsorption properties but relatively lower efficiency for smaller molecules.

The adsorption mechanisms vary with the activator due to differences in surface chemistry and functional groups. ZnCl_2 -treated ACCSW demonstrated excellent heavy metal adsorption through physical adsorption and surface complexation, leveraging its chlorine and zinc-rich active sites. CaCl_2 -treated ACCSW excelled in chemisorption by forming stable complexes with lead (Pb^{2+}) and cadmium (Cd^{2+}), facilitated by calcium oxide and hydroxide groups. Na_2CO_3 -treated ACCSW enhanced ion exchange and precipitation of metals like copper (Cu^{2+}) and nickel (Ni^{2+}) due to its alkaline carbonate functionality. Each activator tailored the carbon surface for specific heavy metal adsorption mechanisms.

ZnCl_2 -treated ACCSW delivered the highest productivity ($3.5 \text{ L}/\text{m}^2/\text{day}$) and efficiency (58%) in solar stills by optimizing porosity, thermal conductivity, and interaction with seawater salts. CaCl_2 -treated ACCSW achieved slightly lower productivity ($3.4 \text{ L}/\text{m}^2/\text{day}$) but was effective in improving water quality through precipitation of impurities like calcium carbonate. Na_2CO_3 -treated ACCSW exhibited the lowest productivity ($3.2 \text{ L}/\text{m}^2/\text{day}$) due to its limited thermal properties, although its basicity contributed to impurity removal.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of Artificial Intelligence

The authors acknowledge that artificial intelligence tools were used only for language editing purposes, such as improving grammar, clarity, and readability of the manuscript. ChatGPT (OpenAI) was utilized exclusively for linguistic refinement and did not contribute to the generation of scientific content, data interpretation, methodological development, results, or conclusions.

All scientific ideas, analyses, experimental designs, results, discussions, and interpretations were fully developed by the authors.

The authors take full human responsibility for the accuracy, originality, and integrity of the entire manuscript.

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Authors' contributions

Nova Risdiyanto Ismail: Conceptualization, Supervision, Methodology, Validation, Writing – review & editing, Project administration, Resources, Writing – original draft, Funding Acquisition.

Silviana: Methodology, Investigation, Data curation, Formal analysis, Adsorptive property testing, Writing – review & editing, Project Administration.

Sabar Setiawidayat: Instrumentation, Solar still performance measurement, Resources, Software, Visualization, Validation.

Purbo Suwandono: Sample preparation, Activated carbon synthesis and chemical activation, Thermal and morphological characterization, Formal analysis, Writing – original draft.

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