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Research Paper

Desalination of Seawater using Pahae Natural Zeolite-Activated Carbon derived from Kepok Banana Peel (*Musa paradisiaca* Linn.)

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Abstract

The escalating demand for freshwater due to increased global population and intensified industrial activities necessitates innovative approaches to water desalination. This study explores the efficacy of a novel composite adsorbent material consisting of Pahae natural zeolite and activated carbon derived from Kepok banana peels for seawater desalination. This research synthesizes and evaluates the composite under varying conditions to ascertain its potential as an effective adsorbent material. Characterization methods included scanning electron microscopy (SEM), energy dispersive X-ray (EDX), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), Brunauer-Emmett-Teller (BET), and salinity removal measurement. The results demonstrated that the 85:15% zeolite to activated carbon ratio exhibited the highest porosity of 61.04% and a significant water absorption capacity of 86.65%. This composition also achieved the most substantial salinity reduction, lowering the initial salinity from 27.70‰ to 18.53‰ with a removal efficiency of 33.10%. SEM analyses revealed a more porous surface morphology at 85:15% which corroborated with the higher salinity removal efficiency. BET results indicated that the optimal pore size and distribution occurred in the 85:15% composition which directly correlated with enhanced adsorption capacities. This study reports the potential of using sustainable materials such as zeolite and agricultural waste-derived activated carbon for cost-effective and environmentally friendly desalination processes. The findings suggest that such composites can be tailored to improve performance and provide a viable solution to the global freshwater scarcity challenge.

Keywords

Natural Zeolite, Activated Carbon, Desalination, Water Treatment, Seawater

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1. INTRODUCTION

In recent decades, the demand for freshwater has surged to unprecedented levels, driven by the burgeoning global population and the intensification of industrial and agricultural activities, leading to a critical scarcity of this essential resource (Guo et al., 2024; Oliver et al., 2021). Over 90% of the water available on Earth is in the form of seawater; therefore, its conversion into freshwater is a befitting solution to fight the freshwater crisis (Curto et al., 2021; Lin et al., 2021). Desalination based on a number of techniques such as reverse osmosis (Ahmed et al., 2021; Fayyaz et al., 2023), electrodialysis (Gohil et al., 2023; Muisa et al., 2020), multi-stage flash distillation (Castro-Munoz, 2023; Muisa et al., 2020), and vapor compression distillation (Muisa et al., 2020; Wen et al., 2020) are widely employed globally. Although these technologies can generate substantial quantities of freshwater, they are often associated with high capital, maintenance, and operational costs, which limit their broader application. Moreover, many of these methods present significant environmental challenges. Consequently, there is an imperative to develop desalination methods that are both cost-effective and environmentally sustainable.

Salinity refers to the concentration of salt in water, which is important factors affecting water usability for drinking, agriculture, and industrial purposes (Rich and Maier, 2015). Desalination, the process of extracting salts and other minerals from seawater, aims to generate potable water (Castro-Munoz, 2023; Fayyaz et al., 2023). Among the various technologies proposed for desalination, those utilizing sorbent materials have garnered significant attention due to their environmentally friendly nature, low operational costs, and minimal ecological footprint (Wajima and Sekihata, 2023; Wibowo et al., 2017a, 2015).

This methodology operates on the principle of adsorption, whereby sorbent materials attract and immobilize undesired ions and molecules. In this process, the sorbent materials provide active sites that facilitate the selective binding and removal of salt ions from seawater, thereby reducing its salinity and enhancing its quality for intended uses.

Zeolite, an inorganic mineral, has garnered significant attention both in Indonesia and globally due to its remarkable adsorptive capabilities (de Magalhaes et al., 2022; Sihombing et al., 2022; Xiao et al., 2024; Luo et al., 2021). This ability arouses exceptional attention for its excellent adsorptive capability (Nasution et al., 2015; Sudibandriyo and Putri, 2020; Susilawati et al., 2018, 2023, 2022), which is primarily as a result of its porous structure and extraordinary physicochemical properties (Khaleque et al., 2020; Susilawati et al., 2021; Wibowo et al., 2023). Zeolite is characterized by a high cation exchange capacity, selectivity for certain cations, and a substantial pore volume (Calabrese, 2019; Zarrintaj et al., 2020). Its amorphous structure, comprising interconnected cavities, facilitates the efficient adsorption of small molecules across a high surface area (Susilawati et al., 2022, 2023). This cation adsorption capacity, which supports catalytic exchange, underpins zeolite's use in various applications, including water filtration and moisture absorption. In water remediation, natural zeolites are outstanding sorbents due to their hydration properties and superior ion-exchange characteristics, which enable the effective removal of heavy metal ions from water systems. Compared to other low- cost adsorptive materials such as activated carbon, fly ash, and clay, natural zeolites offer superior performance. Their non-toxic, abundant, and cost-effective nature has made them highly popular for environmental applications, including water purification, wastewater treatment, and the desalination of contaminated waters.

Materials sourced from Pahae, North Sumatra utilized for water vapor adsorption which exhibited value of 48.05% for the size of 60 Mesh and even better, 68.05% for the size of 200 Mesh (Susilawati et al., 2017). These substantial adsorption values underscore the potential of natural zeolite from Pahae as an effective adsorbent material. Similarly, natural zeolite from Fukushima, Japan, demonstrated a 43% reduction in NaCl content in seawater after ten adsorption cycles, equating to a 4.3% reduction per cycle (Wajima et al., 2010). Further studies have reported even higher salinity reduction rates, such as the findings documented a 4.8% reduction in seawater salinity, or 51.43 g/L, per batch, highlighting its applicability in desalination processes (Wibowo et al., 2017a). While these studies showcase the promising potential of natural zeolites in adsorption applications, they also highlight the challenges of achieving higher efficiency and consistent results. These challenges can be mitigated through further optimization, potentially by incorporating additive materials to enhance the adsorption capabilities of natural zeolites across various environmental applications.

In contemporary environmental preservation efforts, the development of sustainable materials is paramount. Agricultural waste materials such as rice husks (Daffalla et al., 2020; Yefremova et al., 2023), wheat straw (Amen et al., 2020; Tewatia et al., 2021), pumpkin seed (Subbaiah and Kim, 2016), and coffee grounds (Liu et al., 2024; Sukhbaatar et al., 2021) have been explored as alternative adsorbent materials. In this study, Kepok banana peels were selected due to the substantial consumption of Kepok bananas in Indonesia, which generates significant quantities of peel waste. This organic waste presents a challenge for local waste management systems and the broader objective of achieving a circular economy. Consequently, converting Kepok banana peels into activated carbon represents a valorization approach, transforming waste into a valuable product. Activated carbon derived from Kepok banana peels exhibits high surface areas (Setiawan et al., 2023), highly biocompatible, stable, and conductive (Duan et al., 2018). This study demonstrated that activated carbon from Kepok banana peels effectively removed heavy metals such as Mn, Pb, Zn, and Fe from wastewater, achieving removal efficiencies between 52.14% and 99.27% across various pH levels (Khairiah et al., 2021) underscoring its potential as a versatile and efficient adsorbent in water purification applications.

The functionality of zeolite as an adsorption material can be significantly enhanced by integrating it with additional materials that exhibit high adsorption capacities. Activated carbon is one such material, renowned for its extensive surface area and porous structure, which make it highly effective in adsorbing various contaminants. The combination of zeolite and activated carbon can potentially synergize the properties of both materials, thereby optimizing the overall efficiency of seawater desalination. In particular, activated carbon derived from Kepok banana peel, a prevalent agricultural waste in Indonesia, presents a promising candidate for this purpose. The cellulose content and active functional groups in Kepok banana peel are conducive to bio adsorption. Previous research has demonstrated the potential of activated carbon from Kepok banana peel in the adsorption of methylene blue (Setiawan et al., 2023). Building on these findings, this study aims to advance the desalination of seawater using Pahae natural zeolite incorporated with activated carbon derived from Kepok banana peel. The sorbent material mixtures were evaluated based on their physical properties, including porosity, hardness, density, and water absorption. Additionally, advanced characterization techniques such as Scanning Electron Microscopy (SEM), Energy Dispersive X-ray (EDX), X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), and Brunauer-Emmett- Teller (BET) analyses were employed to assess the potential of the composite material as an effective desalination medium. These analyses provided insights into the structural and functional attributes that contribute to the enhanced adsorption performance of the integrated sorbent materials.

2. EXPERIMENTAL SECTION

2.1 Materials

In this study, adsorbent material was synthesized using raw materials that sourced locally from North Sumatra, Indonesia, to exploit the synergistic effects of natural zeolite and Kepok banana peel for seawater desalination. The adsorbent materials were prepared using several chemicals included sulfuric acid, H_2SO_4, 99% (Merck) and aquabidest.

2.2 Collection and Preparation of Natural Zeolite, Kepok Banana Peel and Seawater

The collection of natural zeolites was procured from North Tapanuli Regency, Pahae District, while Kepok banana peels were collected from Medan, reflecting the geographical diversity and natural resources of the region. Natural zeolite, sourced from Pahae District, North Tapanuli, North Sumatra, was manually crushed and ground using a mortar and pestle to reduce its bulk form. The ground zeolite was subsequently sieved through a 100-mesh screen to achieve uniform granularity. The sieved zeolite was thoroughly washed by immersion in distilled water three times and dried in an oven at 100°C for 24 hours. The zeolite underwent a second drying cycle under identical conditions to improve adsorption properties. Chemical activation was performed on the mechanically prepared zeolite by immersing it in 1 M H_2SO_4 within a beaker. This mixture was stirred continuously at 135 rpm and maintained at 80°C for 2 hours. Following this treatment, the zeolite was re-dried under the same oven conditions to ensure optimal activation. Kepok banana peels, collected from Medan, were prepared by removing residual seeds and flesh, cutting the peels into small pieces, and drying them in an oven at 100°C for seven hours. The dried peels were then carbonized at 350°C for 30 minutes in a neutral atmosphere to produce activated carbon. The activated carbon was ground and sieved through a 100-mesh sieve to meet the specifications of SNI No.06-3730-1995. Seawater samples were collected from Cermin Beach in Serdang Bedagai Regency, providing a representative sample for desalination testing. The utilization of local marine water aimed to assess the efficacy of the prepared adsorbent material in real-world conditions. This selection of locally available materials highlights a commitment to leveraging regional resources to address global water scarcity challenges effectively.

2.3 Synthesis of Natural Zeolite-Kepok Banana Peel Activated Carbon as Adsorbent Material

The prepared Pahae zeolite and activated carbon derived from Kepok banana peels were blended in various weight ratios: 100:0%, 95:5%, 90:10%, 85:15%, 80:20%, and 0:100%. The blends were then placed in a YM1832 Yami shaker and agitated for five minutes. Subsequently, distilled water equivalent to 50% v/w of the overall composition was added, followed by further agitation. The mixture was then molded with a size of 3 × 3 × 1 cm using a Hydraulic Press Ytd27-200t at a pressure of 5 tons for ten minutes. This process was repeated for each compositional variant. After air-drying for one week, the samples were sintered at 500°C for four hours to prevent cracking during the physical activation process. The synthesis producing 6 samples that stored in airtight containers until further characterization and adsorption experiments.

This study introduces a novel adsorbent material composed of Pahae natural zeolite and activated carbon from Kepok banana peels, a combination not previously reported in the scientific literature. The research explores the potential of composite material to reduce seawater salinity, an area that has not been extensively investigated. The innovative approach leverages the adsorptive properties of both Pahae natural zeolite and carbonized Kepok banana peels to address the challenge of freshwater scarcity. This research highlights the potential of using locally available, environmentally sustainable resources for desalination applications, contributing to the development of cost-effective and efficient water purification technologies.

2.4 Material Characterizations

The characterization was used to determine the physical properties of the adsorbent materials— namely Pahae natural zeolite and activated carbon derived from Kepok banana peels—in different compositions. These pre-evaluation test consisted of determining porosity, water absorption capacity, hardness, and density of each composite material. The important parameter for determination of adsorbent performance is the porosity. Porosity was calculated using Equation (1), which gives the volume fraction of void spaces inside the sample as:

$$\%\text{Porosity} = \left(\frac{m_w - m_d}{\rho_w \times v_t}\right) \tag{1}$$

where m_w is the wet mass (g), m_d is the dry mass (g), ρ_w is density of water (g/m^3), Vt is sample volume after burning (m^3). Water absorption capacity was determined by Equation (2) in comparing the mass of samples before and after soaking the sample for 24 hours at room temperature; the samples are soaked in the water, which will then give an idea of the ability of the materials to hold water as below:

$$\%\text{Water Absorption Test } = \left(\frac{m_w - m_d}{m_d}\right) \times 100\% \tag{2}$$

where m_w is the wet mass (g), and m_d is dry mass (g). Vickers Hardness method was followed in determining the hardness of the composites, which is a measure of the resistance of the material to physical deformation under pressure. The value of hardness is given as in Equation (3) below:

$$H_v = 1{,}8544\frac{F}{d^2} \tag{3}$$

where F define applied force (N), and d^2 define the square of the indentation diagonal length in (mm). Density measurements, which provide the mass per unit volume of the adsorbents, were calculated using Equation (4):

$$\text{Density} = \frac{m}{V} \tag{4}$$

where m is the dry mass (g), and V is the sample volume after burning (cm^3). These tests were important for gaining the basic knowledge of the physical features of the materials, guiding the optimization of the adsorbent composition to achieve effective salinity reduction.

2.5 Instrumentations

The sample of adsorbent materials, composed of Pahae natural zeolite and activated carbon derived from Kepok banana peels were examined with a JEOL JSM6390 scanning electron microscope and an Oxford Instruments energy-dispersive X-ray analyzer to determine key features such as morphology and elemental composition. A Philips PW 1050 X-ray diffractometer was used to analyze the crystalline phases in the samples over a wavenumber range, scanning 2θ angles from 7 to 70°. FTIR analyses were carried out using a PerkinElmer System IR 2000 spectrometer, with wavenumber range of 4,000-400 cm^{-1} using KBr pellet technique for 100 scans. The specific surface area of the samples was calculated by the BET method which uses a relative pressure range from 0.05 to 0.2. The total pore volumes and pore size distribution at $P/P_0 = 0.99$, using the N_2 isotherm data with the Non-Local Density Functional Theory method. The average pore size was calculated using the formula 4 V/A, where V is the pore volume and A is the surface area. Meanwhile, the methodology for analyzing mineral contents adheres to the procedures outlined in the 2020 SNI Catalog of Environmental Quality Testing Methods, published by the Center for Environmental and Forestry Standardization. Metals were quantified using Atomic Absorption Spectroscopy, with specific tests for sodium (Na^+) under SNI code 06.2428.1991, magnesium (Mg^{2+}) under SNI code 06-6989.55-2005, calcium (Ca^{2+}) under SNI code 06-6989.56-2005, and potassium (K^+) under SNI code 6989.69:2009. Additionally, the analysis of non-metallic substances included chlorine (Cl^-) using the argentometric (Mohr) method according to SNI code 06-6989.19-2004, and sulfate ($SO_4{}^{2-}$) was tested using the turbidimetric method described in SNI code 06-6989.20-2004. This comprehensive set of analytical tools provided a detailed understanding of the minerals of seawater, the physical and chemical properties of the adsorbent material, which was crucial for evaluating its efficacy in seawater desalination.

2.6 Salinity Removal Studies

A series of analysis was conducted to evaluate salinity removal performance of adsorbent material. Prior to the desalination process, the characteristic of seawater was analyzed such as Total Dissolved Solids (TDS), hardness, electrical conductivity, and salinity. After that initial characterization, the adsorbent materials comprised of activated Pahae natural zeolite and activated carbon from Kepok banana peels, were immersed in the seawater in transparent bottles. It was then submitted to mechanical shaking to facilitate the adsorption process of materials. A Mettler Toledo SG7-FK2 Salinometer utilized to measure salinity before the immersion and after 48 hours mixtures. This method used to identify the value of seawater salinity at room temperature (25°C) and atmospheric pressure. The reduction in salinity of seawater, Rs, was measured according to Equation (5):

$$R_s = C_o - C_e \tag{5}$$

where C_o is the initial concentration of salinity, and C_e is the concentration of salinity at equilibrium. The percentage reduction efficiency of salinity was calculated from Equation (6).

$$\%\text{Salinity Removal Efficiency} = \frac{C_o - C_e}{C_o} \times 100 \tag{6}$$

Thereby, based on equations, the effectiveness of the adsorbents to reduce the salinity of seawater can be analyzed and calculated. This methodological approach helps in the evaluation of desalination capacity of the adsorbent materials together with the possibility of optimization of the desalination process for practical applications.

3. RESULT AND DISCUSSION

3.1 Morphological Analysis

Scanning Electron Microscopy (SEM) was utilized to investigate surface morphology of composite adsorbents composed of Pahae zeolite and activated carbon derived from Kepok banana peels. Figure 1(a-f) provides a comprehensive depiction of the morphological characteristics of these composites, with varying ratios ranging from 100:0%, 95:5%, 90:10%, 85:15%, 80:20%, to 0:100%. The SEM images clearly demonstrate a morphological transition as the proportion of activated carbon increases. Figure 1(a), representing the 100% Pahae zeolite, shows a smooth and relatively homogeneous surface with some minor cracks, typical of crystalline zeolitic materials. This structure exhibits small porosity and less frequent pore openings.

Figure 1(b) to 1(e), illustrating decreasing proportions of zeolite from 95% to 80% and increasing proportions of activated carbon, reveal a gradual increase in surface roughness and porosity. This change is evidenced by the frequent pores, alongside a more textured surface. These structural changes are attributed to the inherent porous nature of the activated carbon derived from banana peels, which disrupts the dense zeolitic matrix, leading to increased surface area and potentially enhanced adsorptive properties.

Interestingly, Figure 1(f), which shows the 0:100% activated carbon composition, depicts a significantly more compact and dense surface structure compared to the 90:10%, 85:15%, and 80:20% compositions. This observation suggests that at full concentration, the activated carbon exhibits a tendency to form a tightly packed structure, which may lead to decreased porosity. This compactness is likely a result of the thermal processing at 500°C, which could induce changes in the carbon's structural integrity, leading to a reduction in the number of pores (Li

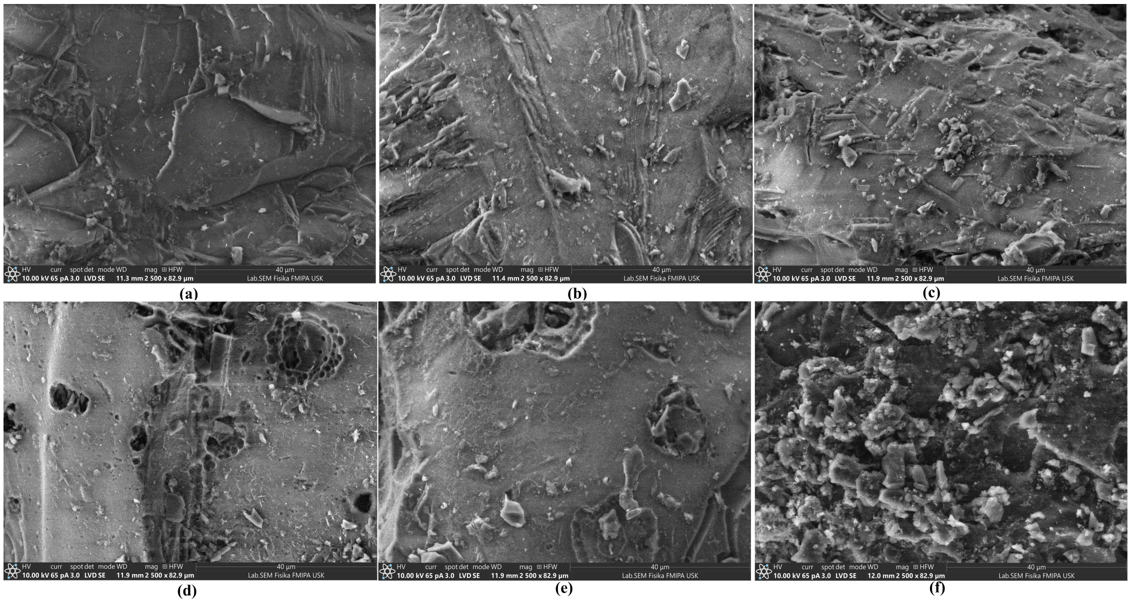
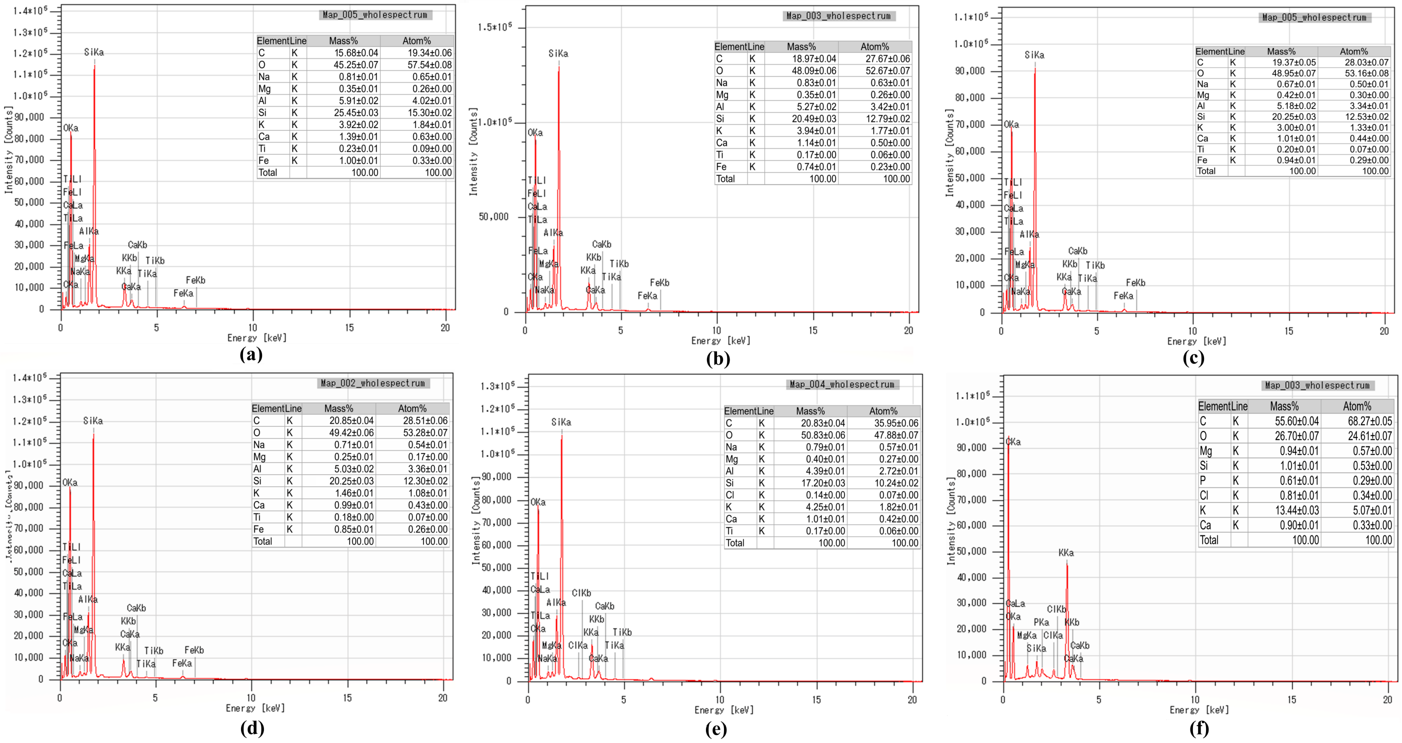


Figure 1. SEM Images of Adsorbent Made from Pahae Natural Zeolite and Activated Carbon Derived from Kepok Banana Peels with Variation Composition of (a) 100:0; (b) 95:5; (c) 90:10; (d) 85:15; (e) 80:20 and (f) 0:100



(a) Map_005_wholespectrum

Element	Line	Mass%	Atom%
C	K	15.68±0.04	19.34±0.06
O	K	45.25±0.07	57.54±0.08
Na	K	0.81±0.01	0.65±0.01
Mg	K	0.35±0.01	0.26±0.00
Al	K	5.91±0.02	4.02±0.01
Si	K	25.45±0.03	15.30±0.02
K	K	3.92±0.02	1.84±0.01
Ca	K	1.39±0.01	0.63±0.00
Ti	K	0.23±0.01	0.09±0.00
Fe	K	1.00±0.01	0.33±0.00
Total		100.00	100.00

(b) Map_003_wholespectrum

Element	Line	Mass%	Atom%
C	K	18.97±0.04	27.67±0.06
O	K	48.09±0.06	52.67±0.07
Na	K	0.83±0.01	0.63±0.01
Mg	K	0.35±0.01	0.26±0.00
Al	K	5.27±0.02	3.42±0.01
Si	K	20.49±0.03	12.79±0.02
K	K	3.94±0.01	1.77±0.01
Ca	K	1.14±0.01	0.50±0.00
Ti	K	0.17±0.00	0.06±0.00
Fe	K	0.74±0.01	0.23±0.00
Total		100.00	100.00

(c) Map_005_wholespectrum

Element	Line	Mass%	Atom%
C	K	19.37±0.05	28.03±0.07
O	K	48.95±0.07	53.16±0.08
Na	K	0.67±0.01	0.50±0.01
Mg	K	0.42±0.01	0.30±0.00
Al	K	5.18±0.02	3.34±0.01
Si	K	20.25±0.03	12.53±0.02
K	K	3.00±0.01	1.33±0.01
Ca	K	1.01±0.01	0.44±0.00
Ti	K	0.20±0.01	0.07±0.00
Fe	K	0.94±0.01	0.29±0.00
Total		100.00	100.00

(d) Map_002_wholespectrum

Element	Line	Mass%	Atom%
C	K	20.85±0.04	28.51±0.06
O	K	49.42±0.06	53.28±0.07
Na	K	0.71±0.01	0.54±0.01
Mg	K	0.25±0.01	0.17±0.00
Al	K	5.03±0.02	3.36±0.01
Si	K	20.25±0.03	12.30±0.02
K	K	1.46±0.01	1.08±0.01
Ca	K	0.99±0.01	0.43±0.00
Ti	K	0.18±0.00	0.07±0.00
Fe	K	0.85±0.01	0.26±0.00
Total		100.00	100.00

(e) Map_004_wholespectrum

Element	Line	Mass%	Atom%
C	K	20.83±0.04	35.95±0.06
O	K	50.83±0.06	47.88±0.07
Na	K	0.79±0.01	0.57±0.01
Mg	K	0.40±0.01	0.27±0.00
Al	K	4.39±0.01	2.72±0.01
Si	K	17.20±0.03	10.24±0.02
Cl	K	0.14±0.00	0.07±0.00
K	K	4.25±0.01	1.82±0.01
Ca	K	1.01±0.01	0.42±0.00
Ti	K	0.17±0.00	0.06±0.00
Total		100.00	100.00

(f) Map_003_wholespectrum

Element	Line	Mass%	Atom%
C	K	55.60±0.04	68.27±0.05
O	K	26.70±0.07	24.61±0.07
Mg	K	0.94±0.01	0.57±0.00
Si	K	1.01±0.01	0.53±0.00
P	K	0.61±0.01	0.29±0.00
Cl	K	0.81±0.01	0.34±0.00
K	K	13.44±0.03	5.07±0.01
Ca	K	0.90±0.01	0.33±0.00
Total		100.00	100.00

Figure 2. EDX Test Results of Adsorbent Made from Pahae Natural Zeolite and Activated Carbon Derived from Kepok Banana Peels with Variation Composition of (a) 100:0; (b) 95:5; (c) 90:10; (d) 85:15; (e) 80:20 and (f) 0:100

et al., 2024; Shoumkova and Stoyanova, 2013). These morphological results are crucial for adsorptive applications, as the increase in porosity and surface area directly correlates with the ability of the adsorbents to capture and retain chemical species. Therefore, the morphological analysis supports the hypothesis that integrating activated carbon with Pahae zeolite enhances the composite's adsorptive properties, with increasing proportions of activated carbon leading to increased surface

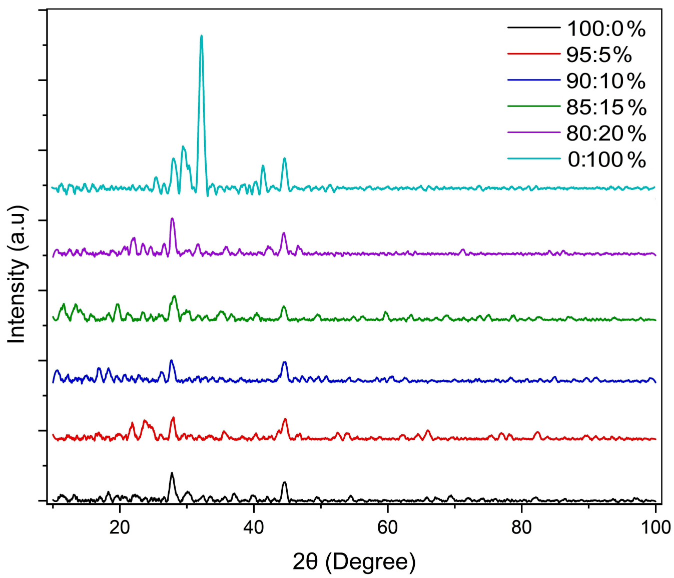


Figure 3. Diffraction Pattern of Adsorbent Made from Pahae Natural Zeolite and Activated Carbon Derived from Kepok Banana Peels with Variation Composition

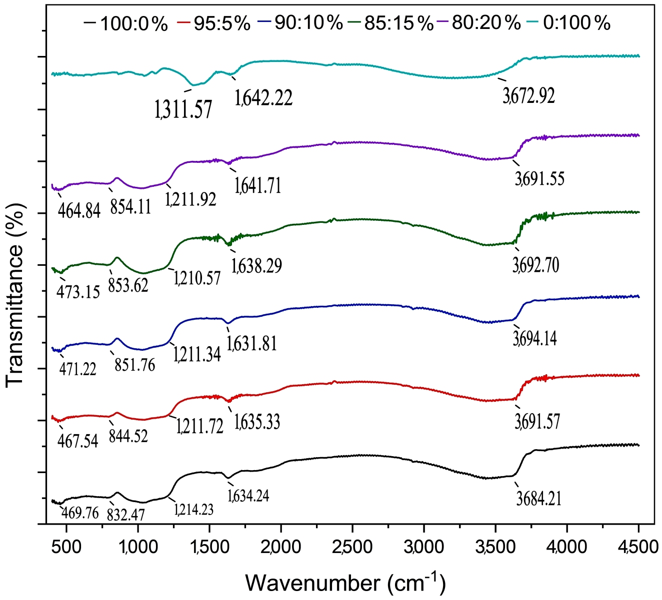


Figure 4. FTIR Spectra of Adsorbent Made from Pahae Natural Zeolite and Activated Carbon Derived from Kepok Banana Peels with Varying Compositions

area and porosity, critical factors in improving adsorption efficiency (Susilawati et al., 2017, 2018, 2022).This suggests that the composite material can be tuned for specific adsorption requirements by adjusting the zeolite to carbon ratio, offering a versatile solution for desalination applications. Further quantitative analysis of pore size distributions and surface areas, possibly via BET surface area analysis, would complement these findings and provide a fuller understanding of the materials' adsorptive properties.

3.2 EDX Analysis

Energy-dispersive X-ray spectroscopy (EDX) was employed to determine the elemental composition of the adsorbent materials, as this composition is a critical determinant of their adsorptive capacity. Figure 2(a-f) displays the EDX spectra for compositions varying from 100:0%, 95:5%, 90:10%, 85:15%, 80:20%, to 0:100%. The spectra illustrate significant variations in the elemental composition, particularly for silicon (Si), aluminum (Al), carbon (C), and oxygen (O), across different adsorbent formulations. In the pure zeolite composition (100:0%), the spectra predominantly show high peaks for Si and O, reflecting the siliceous nature of the material. The presence of Al is also notable, which is characteristic of the aluminosilicate framework of zeolites. As the percentage of carbon (derived from banana peels) in the adsorbent increases, there is a discernible increase in the carbon peaks within the spectra. For instance, in the 95:5% composition, the carbon content visibly increases compared to the 100% zeolite, indicating the beginning of carbon incorporation into the zeolite matrix. This trend continues more markedly in the compositions from 90:10% to 80:20%, where the carbon content progressively dominates the spectra. By the 0:100% composition, where the adsorbent is purely derived from banana peel activated carbon, the EDX spectrum is primarily characterized by carbon and oxygen, with minimal peaks of silicon or aluminum. Correspondingly, the intensity of the oxygen peaks increases, reflecting bigger pores on the surface of adsorbent materials. This corresponds with literature, which indicates that higher oxygen content of the material will result in the creation of more cavities on the material's surface (Kordala and Wyszkowski, 2024). These findings highlight the significant impact of the compositional variation on the elemental content of the adsorbents, which in turn influence desalination capability in reduction of seawater salinity.

3.3 XRD Analysis

The adsorbent materials compositions of pure zeolite and activated carbon from Kepok banana peels ranging from 100:0% to 0:100% were characterized using X-ray Diffraction (XRD) analysis to determine the presence of crystalline and amorphous regions in their structure. As depicted in Figure 3, significant differences in peak intensity and position reflect structural variations within the adsorbent materials as the composition of zeolite and activated carbon changes. In the sample with 100% zeolite, the high intensity of peaks indicates a highly crystalline structure, which is essential for the ion-exchange and adsorption processes used in desalination, particularly effective for trapping specific ions in seawater. However, as the proportion of activated carbon increases, these peaks diminish, indicating a reduction in crystalline regions and an increase in amorphous characteristics. This shift towards amorphous struc-

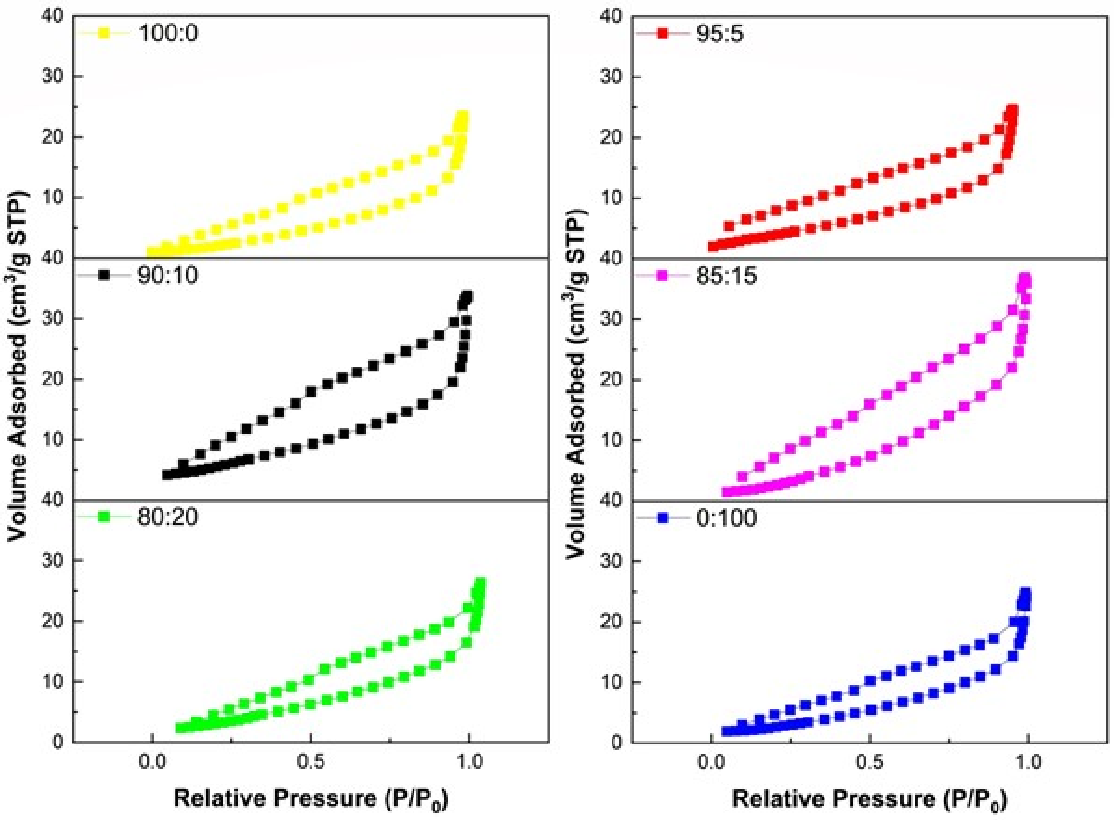


Figure 5. N_2 Adsorption-Desorption Isotherm of Pahae Natural Zeolite and Activated Carbon Derived from Kepok Banana Peels with Variation Composition

tures, evident from the broad, humped backgrounds in XRD patterns for higher activated carbon compositions, suggests a broader range of adsorption capabilities. Activated carbon, being amorphous, can adsorb a variety of molecule sizes and shapes, potentially useful for removing diverse contaminants in more complex saline waters or waters with high levels of organic matter. Nonetheless, this comes potentially at the expense of the high selectivity provided by the crystalline zeolite for specific ions. The XRD data reveals that a blend of zeolite and activated carbon could leverage the high selectivity of crystalline zeolite for certain ions, with the broad-spectrum adsorptive capacity of amorphous activated carbon.

Determining the optimal composition depends on specific desalination requirements, including the desired purity of the water, the types of impurities prevalent, and efficiency requirements. Overall, the structural insights provided by the XRD analysis are invaluable for tailoring adsorbent materials to enhance the performance of desalination processes, suggesting that a strategic combination of crystalline and amorphous phases in adsorbents can effectively reduce seawater salinity while improving the overall quality of the produced water.

3.4 FTIR Analysis

Fourier Transform Infrared (FTIR) analysis was conducted to determine the functional groups of adsorbent materials comprised of pure zeolite and activated carbon from Kepok banana peels, with varying compositions from 100:0% to 0:100%. The FTIR spectra, as shown in Figure 4, reflect distinct changes in transmittance across different wavenumber ranges, which helps to elucidate the chemical characteristics and potential adsorption capabilities of the adsorbents. The transmittance peaks observed in the FTIR spectra are indicative of specific functional groups that are crucial for the adsorption processes involved in desalination. For instance, broad bands in the region around 3,400 cm^{-1}, predominantly seen in all samples, are typical of O−H stretching vibrations, suggesting the presence of hydroxyl groups. These groups are known for their role in water molecule interactions, which can enhance the adsorption of water-soluble contaminants and ions typically found in seawater (White, 2024).

As the percentage of activated carbon increases in the samples, there is a noticeable shift in peak patterns and intensities. Activated carbon, being rich in carbon content, typically shows bands associated with C−H stretching in the range of 2,800-3,000 cm^{-1}, and these are observed to become more prominent in samples with higher activated carbon content. Moreover, the

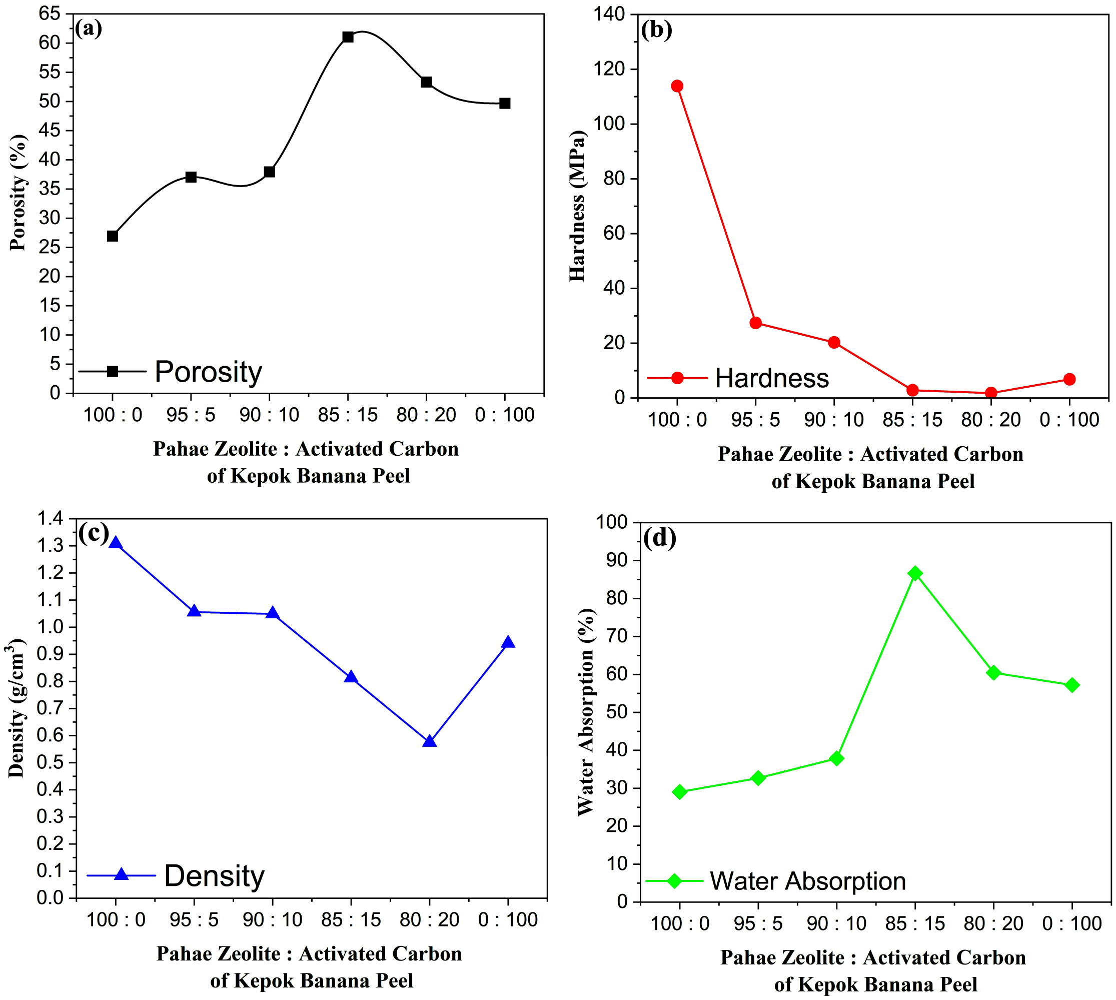


Figure 6. Porosity Graph of Various Adsorbent Composition (a), Hardness Graph of Various Adsorbent Composition (b), Density of Various Adsorbent Composition (c), Water Absorption of Various Adsorbent Composition with Variation Composition (d)

presence of peaks around 1,630 cm^{-1}, associated with C=O stretching, indicates the presence of carbonyl groups. These functional groups can participate in complexation with metal ions, which is a valuable property in the context of desalination, as it aids in the removal of heavy metal ions from saline waters. The overall effect of these functional groups, as revealed by the FTIR analysis, on the desalination process is significant. The hydroxyl and carbonyl groups can improve the adsorption of polar contaminants and ions, while the increased hydrophobicity from the activated carbon can enhance the removal of non-polar substances, such as certain organic compounds. Therefore, the FTIR results suggest that blending zeolite with activated carbon not only adjusts the physical adsorption dynamics but also chemically tailors the adsorbents for enhanced performance in reducing seawater salinity. This tailored approach enables the creation of more efficient adsorbent materials that can address the diverse challenges posed by different impurities in seawater, thus improving the efficacy and efficiency of desalination processes.

3.5 BET Analysis

Brunauer-Emmett-Teller (BET) results present N_2 adsorption-desorption and the average pore sizes of composite materials derived from Pahae Zeolite and activated carbon from Kepok banana peels, as this composition is a critical determinant of their adsorptive capacity. Table 1 listed the BET result for compositions varying from 100:0%, 95:5%, 90:10%, 85:15%, 80:20%, to 0:100%. The variations in pore size across different compositions directly influence the efficacy of the adsorbents in the desalination process. Notably, the composition with 85:15% zeolite to activated carbon demonstrates the largest average pore size of 84.67 Å, making it the most effective in desalination. Larger pore sizes in this composition can accommodate more extensive ion exchange and adsorption processes, crucial for effectively capturing and removing the diverse range of salts and minerals found in seawater. This larger pore structure likely facilitates faster water flow through the adsorbent material, enhancing the overall efficiency of the salt removal process. Conversely, the 100:0% composition, which solely

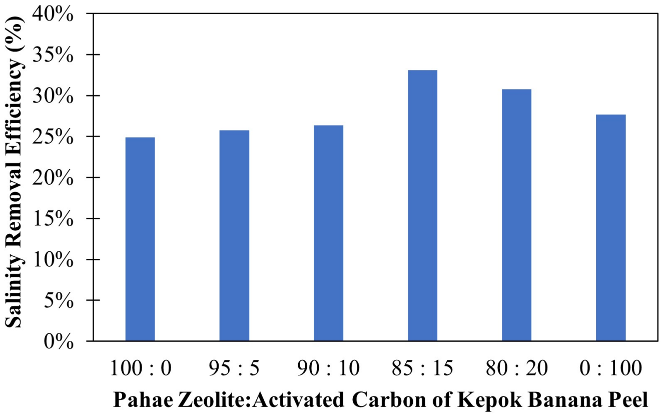


Figure 7. Salinity Removal Efficiency of Seawater Desalination Using Pahae Natural Zeolite and Activated Carbon Derived from Kepok Banana Peels with Variation Composition

consists of Pahae Zeolite, shows a significantly smaller average pore size of 49.26 Å. The smaller pore size limits the rate and volume of seawater that can interact with the active sites within the material, reducing its capacity to efficiently adsorb and remove salt ions. Moreover, the specific surface areas (SBET) and total pore volumes (VTotal) of these composites exhibit substantial variations that are also reflective of the changes in composite ratios. The sample containing 85:15% zeolite to activated carbon shows the highest specific surface area (20.67 m^2/g) and total pore volume (0.05564 cm^3/g), suggesting a high availability of adsorptive sites and a significant porosity, which are favourable for adsorption processes. This increase in surface area and pore volume with a higher proportion of activated carbon is consistent with the material's intrinsic properties, as activated carbon typically has a more developed pore network than zeolite.

The external surface area (SExt) and micropore volume (VMicro) also provide insight into the textural characteristics of these composites. As seen from the data, there is a general increase in both SExt and VMicro as the percentage of activated carbon increases. For instance, the composite with 85:15% ratio displays a higher external surface area (21.16 m^2/g) compared to that of the 100:0% zeolite (10.96 m^2/g), highlighting the influence of activated carbon in developing more accessible external surfaces which are beneficial for the adsorption of larger molecules. In terms of practical applications, these variations in material characteristics are critical. For example, in desalination processes where adsorption kinetics and the efficiency of ion exchange are crucial, the balance between micropore accessibility and the mesoporosity (reflected by average pore sizes and VMeso) must be optimized. The data shows that compositions with higher activated carbon content not only facilitate larger pore sizes but also enhance the volume of mesopores, which supports faster kinetics for the adsorption of saline ions from water.

The observed trend where larger average pore diameters (DPore), such as the 169.34 Åin the 85:15% composite, correspond to enhanced mesoporosity, suggests that these materials are particularly suitable for targeting larger molecular structures typically found in brackish water and seawater. This makes them excellent candidates for not only traditional adsorption applications but also for more demanding environmental applications such as the removal of heavy metals and larger organic pollutants, which require access to larger pore structures. This result highlights the limitations of using pure zeolite in scenarios where a higher adsorptive capacity and faster filtration rates are required, as might be the case in industrial-scale desalination processes. This trend suggests that the incorporation of activated carbon into the zeolite matrix plays a pivotal role in enhancing the material's structural characteristics, such as pore size, which in turn improves its performance in desalination applications.

The BET analysis illustrated in the attached Figure 5 provides a detailed evaluation of nitrogen adsorption-desorption isotherms for composites of Pahae Zeolite and activated carbon derived from Kepok banana peels across different compositional ratios from 100:0% to 0:100%. As shown in Figure 5, the volume of nitrogen adsorbed increases with the relative pressure P/P_0, with all materials exhibiting Type IV isotherms characteristic of mesoporous materials. This type of isotherm typically indicates the presence of capillary condensation occurring in mesoporous structures, followed by hysteresis loops suggesting pore network irregularities and connectivity. A critical observation from the data is the influence of activated carbon content on the adsorption capacity. As the proportion of activated carbon increases from 0% to 20%, there is a discernible enhancement in the adsorption capacity at higher relative pressures, suggesting that the activated carbon contributes significantly to the overall porosity and specific surface area of the composites. This is attributed to the high porosity of the activated carbon itself, which enhances the composite's ability to adsorb larger volumes of gas. The isotherms for samples with higher percentages of activated carbon 85:15% show a steeper rise in adsorption volume near complete saturation (P/P_0 close to 1), indicating the presence of larger pores or a wider pore size distribution capable of accommodating more gas molecules at higher relative pressures. Furthermore, the 100:0% zeolite composite shows a lower adsorption capacity across all relative pressures, underscoring the role of the activated carbon's microporous structure in enhancing gas adsorption under these experimental conditions. The results elucidate the impact of composite formulation on adsorption properties, with the activated carbon component significantly enhancing the porosity and adsorption capacity of the materials. aligns with the needs for more efficient desalination processes capable of handling high salinity levels typical of seawater.

3.6 Physical Properties of Adsorbent Materials

A pre-evaluation was conducted to assess the physical properties of adsorbent materials- specifically Pahae natural zeo-

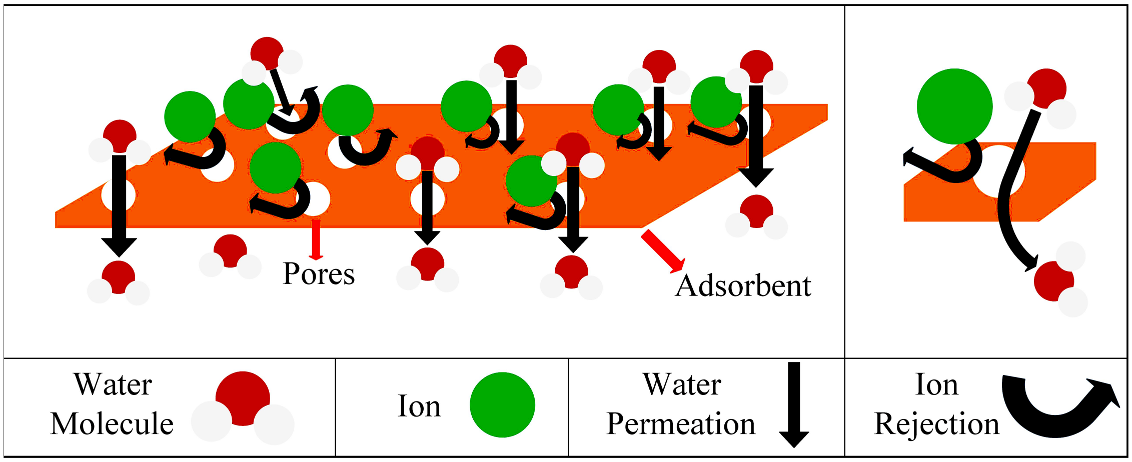


Figure 8. Seawater Desalination Mechanism Using Pahae Natural Zeolite and Activated Carbon Derived from Kepok Banana Peels with Variation Composition

Table 1. Brunauer–Emmett–Teller (BET) Result

Pahae Zeolite: Activated Carbon of Kepok Banana Peel	Average Pore Size [Å]	SBET [m^2/g]	SExt [m^2/g]	VMicro [cm^3/g]	VMeso [cm^3/g]	VTotal [cm^3/g]	DPore [Å]
100 : 0	49.26 Å	10.56	10.96	0.00320	0.03383	0.03590	49.26
95 : 5	51.13 Å	9.13	13.44	0.00353	0.03594	0.04066	111.72
90 : 10	55.86 Å	13.86	14.56	0.00488	0.05060	0.05260	154.28
85 : 15	84.67 Å	20.67	21.16	0.00780	0.05244	0.05564	169.34
80 : 20	78.27 Å	12.34	14.42	0.00472	0.04413	0.05211	136.30
0 : 100	77.14 Å	13.63	14.81	0.00207	0.03300	0.03735	102.28

lite and activated carbon derived from Kepok banana peels-in varying compositions. These preliminary tests focused on determining the porosity, water absorption capacity, hardness, and density of each composite which depicted in Figure 6(a-d), respectively. This systematic analysis provided a foundational understanding of each material's specific attributes to understand their structural characteristics and performance potential in desalination processes. Porosity is calculated as a ratio of void volume to the overall volume. It is determined by the difference in mass between the wet mass of each sample and its dry mass, and this result is correlated with the density and volume of water. It is one of the very important parameters for these materials, affecting their adsorption efficiency. Figure 6a exhibits the porosity values for compositions varying from 100:0%, 95:5%, 90:10%, 85:15%, 80:20%, to 0:100%. At the peak of this graph, the composition with 85:15% zeolite to activated carbon demonstrates the highest porosity at 61.04%. This high porosity suggests a greater volume of void spaces within the adsorbent material, which is beneficial for enhancing the surface area available for salt and mineral ion adsorption from seawater (Vasconcelos et al., 2023). The increased porosity facilitates more extensive contact between the adsorbent and the saline water, allowing for more effective salt capture and removal, which explains why this composition was found to be the most effective. On the other hand, the 100:0% composition, which consists solely of zeolite, shows significantly lower porosity, near 30%. This lower porosity limits the volume of void spaces available for water interaction, which in turn constrains the material's ability to adsorb salts efficiently. On the other hand, the increased porosity not only supports better salt removal efficiency but also may improve the kinetics of the adsorption process, as more water can permeate through the porous structure, inging more ions into contact with adsorptive sites. Thus, optimizing the porosity of adsorbent materials by adjusting their composite ratios is a crucial strategy for developing more effective desalination technologies.

The results from the hardness tests conducted on adsorbent materials with different compositions presented in Figure 6b. Notably, the 100:0% composition, despite its high hardness, was the least effective for desalination, whereas the 85:15% composition, which demonstrated a moderately lower hardness, was the most effective. The higher hardness in the 100:0% composition, primarily composed of Pahae Zeolite, suggests a denser and more tightly packed crystalline structure. While this characteristic typically confers durability and resistance to mechanical wear, it also results in smaller, less accessible pore sizes. These smaller pores are less effective at facilitating the flow of water and interaction with the adsorptive sites necessary for efficient ion exchange and salt removal, which are crucial processes in desalination. Conversely, the 85:15% composition, which includes a significant proportion of activated carbon, exhibits a balance of hardness and pore accessibility. While the hardness is somewhat reduced compared to the pure zeolite, the inclusion of activated carbon enhances the pore structure, resulting in larger and more open pores. This increase in porosity allows for greater water throughput and more extensive contact with adsorptive sites, significantly improving the removal of dissolved salts from seawater.

Figure 6c. presents the density values of different compositions of adsorbent material. The density values in g/cm^3 provide insight into how the physical characteristics of these materials are shaped by composition. Notably, the 100:0% composition, consisting solely of Pahae Zeolite, shows the highest density. This high density is reflective of a tightly packed crystalline structure, which, while robust, results in smaller and less accessible pores. In contrast, the 85:15% composition, which blends zeolite with 15% activated carbon, shows a considerably lower density. This reduction in density indicates a less compact material structure, leading to larger and more accessible pores. This decrease in density correlates with an increase in porosity, which typically improves adsorption capacities by providing more surface area and accessible sites for ion exchange. Figure 6d. illustrates the water absorption capacities of adsorbent materials. These results show a clear trend where the 85:15% composition exhibits the highest water absorption capacity, which correlates strongly with enhanced desalination performance. The 100:0% composition, which consists solely of Pahae Zeolite, demonstrates the lowest water absorption capacity. This characteristic is largely due to the tightly packed crystalline structure of zeolite, which results in smaller pore sizes. These smaller pores limit the material's ability to absorb water, thereby reducing its effectiveness in desalination processes where water permeability and ion exchange are critical.

3.7 Desalination of Seawater Analysis

The characteristics of raw seawater details presented in Table 2 while the characteristics after desalination of seawater listed in Table 3. Table 2 reveals that the raw seawater sample exhibits high levels of dissolved solids, hardness, and salinity, which are indicative of the typical characteristics of seawater. The total dissolved solids (TDS) concentration of 17,190 mg/L is substantial and presents a significant challenge for desalination processes, as it indicates the presence of a high concentration of dissolved salts and minerals. The water hardness, measured at 223.12 mg/L, reflects a moderate level of calcium and magnesium ions, which are likely to cause scaling in desalination membranes and other equipment if not addressed adequately. Electrical conductivity, recorded at 30,600 μS/cm, is directly related to the high ion content in the seawater and can be used as an indirect measure of the salinity. The salinity, expressed as 27.70‰, also highlights the considerable amount of dissolved salts, although it is slightly lower than the average oceanic salinity, which is typically around 35‰. In terms of specific ionic composition, Chloride ions (Cl^-) concentration is particularly high at 20,423 mg/L, which is expected as chloride ions are the predominant anion in seawater. Sodium ions (Na^+) measured at 11,143 mg/L, are also abundant and play a major role in the overall salinity and conductivity of the water. Sulfate ions (SO_4^{2-}) at 2,955 mg/L, contribute to the water's total ionic content and must be carefully managed to avoid potential scaling issues, especially in combination with calcium and magnesium ions. The concentrations of Mg^{2+} at 1,357 mg/L and Ca^{2+} at 481.91 mg/L indicate the presence of hardness-causing ions, which are known to be challenging in water treatment processes, particularly in desalination systems. Lastly, Potassium ions (K^+) ion while present at a lower concentration of 433.47 mg/L, can still affect water quality and should be considered in the overall desalination process.

Table 2. Characteristic of Raw Seawater

Parameters/Chemical Composition	Unit	Result
TDS	mg/L	17,190
Hardness of water	mg/L	223.12
Electrical Conductivity	μS/cm	30,600
Initial Concentration of Salinity (Co)	‰	27.70
Cl^-	mg/L	20,423
Na^+	mg/L	11,143
SO_4^{2-}	mg/L	2,955
Mg^{2+}	mg/L	1,357
Ca^{2+}	mg/L	481.91
K^+	mg/L	433.47

Table 3 shows the characteristics of seawater after the desalination process using different combinations of Pahae Zeolite and activated carbon derived from Kepok banana peel. These results highlight the effectiveness of the various ratios in reducing the total dissolved solids (TDS), hardness, and ion concentrations from the initial seawater characteristics. The combination of Pahae Zeolite and activated carbon significantly reduced the TDS across all samples, with the best reduction observed in the 85:15 ratio, where TDS was brought down to 895.21 mg/L. The ratio of 100% Pahae Zeolite resulted in the highest of 1,637 after desalination, while the activated carbon alone (0:100 ratio) achieved a TDS of 960.44 mg/L, demonstrating its substantial contribution to TDS reduction even in the absence of zeolite. Hardness reduction was observed across all samples, the lowest hardness, 185.93 mg/L, was achieved with the 85:15 ratio, showing a significant decrease from the initial 223.12 mg/L. The hardness values after desalination are in line with moderate water hardness classifications, but some combinations still produced higher residual hardness, such as the 80:20 and 0:100 ratios, which resulted in 202.84 mg/L and 212.50 mg/L, respectively. This indicates that zeolite plays a key role in hardness reduction whereby its ion-exchange capacity plays important role particularly for calcium and magnesium ions. Meanwhile, the lowest conductivity value was recorded at 1,214 μS/cm for the 85:15 ratio, a

Table 3. Characteristic of Seawater After Desalination

Pahae Zeolite: Activated Carbon of Kepok Banana Peel	Parameters			Chemical composition (mg/L)					
	TDS	Hardness of Water	Electrical Conductivity	Cl^-	Na^+	SO_4^{2-}	Mg^{2+}	Ca^{2+}	K^+
100 : 0	1,637	191.19	1,832	1,011	552.83	537.34	67.02	433.24	21.76
95 : 5	1,081	195.38	1,515	615.24	336.92	501.55	58.29	398.06	13.47
90 : 10	1,061	194.02	1,381	357.31	195.07	477.04	50.11	367.44	8.51
85 : 15	895.21	185.93	1,214	272.76	148.77	321.15	43.28	301.31	6.69
80 : 20	914.97	202.84	1,450	323.14	176.21	336.30	45.67	332.57	7.58
0 : 100	960.44	212.50	1,493	283.50	154.47	374.56	42.54	391.62	6.14

substantial improvement compared to the raw seawater's conductivity of 30,600 μS/cm. This suggests that the desalination is effective in removing charged ions from the seawater. The activated carbon alone achieved a conductivity of 1,493 μS/cm, highlighting its ability to reduce ion content to a lesser extent compared to combinations with zeolite.

The characteristics of seawater after the desalination process exhibits reduction after treatment for Cl^- concentration, whereby 85:15 ratio showed the best performance, reducing chloride levels to 272.76 mg/L, while the 0:100 ratio (pure activated carbon) managed to reduce chloride to 283.50 mg/L. Na^+ in the raw seawater were also significantly reduced whereby 85:15 and 90:10 ratios were most effective, lowering sodium concentrations to 148.77 mg/L and 195.07 mg/L, respectively. Activated carbon on its own was slightly less effective, with Na+ concentration of 154.47 mg/L, but still within acceptable limits. initially at 2,955 mg/L, were also notably reduced across all filter compositions. The lowest SO_4^{2-} concentration was achieved with the 85:15 ratio, where it was reduced to 321.15 mg/L while the highest of 537.34 mg/L produced from 100 :0 which is pure zeolite. Magnesium and calcium ions were substantially reduced after treatment lowering magnesium to 43.28 mg/L and calcium to 301.31 mg/L which produced from 85:15 ratio. Potassium ions (K^+), initially measured at 433.24 mg/L, were reduced significantly in all treated samples, with the best performance observed for the 85:15 ratio, which brought potassium down to 6.69 mg/L. Overall, the combination of Pahae Zeolite and activated carbon from Kepok banana peel shows promising potential for reducing TDS, hardness, and ion concentrations in seawater. The 85:15 ratio, in particular, consistently demonstrated the best performance across most parameters while pure zeolite 100:0 showed poor performance compared to the others.

Table 4 focuses on the reduction of seawater salinity using different compositions of Pahae Zeolite and activated carbon from Kepok banana peels. From the data in Table 4, it is clear that different adsorbent compositions yield varying levels of effectiveness in reducing seawater salinity after four hours of immersion. The best performing composition, 85:15 (zeolite to activated carbon), achieved the highest salinity reduction, bringing the salinity concentration down to 18.53‰ from the initial 27.70‰, and reaching a salinity removal efficiency of 33.10%. In contrast, the 100:0 composition (pure zeolite) was the least effective, reducing the salinity only to 20.80‰, with a salinity removal efficiency of 24.91%.

Table 4. Salinity Reduction of Seawater from Various Adsorbent Materials

Pahae Zeolite : A ctivated Carbon of Kepok Banana Peel	Concentration Equilibrium (Ce) (‰)	Reduction of Seawater Salinity (Rs) (‰)
100 : 0	20.80	6.90
95 : 5	20.56	7.14
90 : 10	20.40	7.30
85 : 15	18.53	9.17
80 : 20	19.18	8.52
0 : 100	20.03	7.67

Correlating these results with the BET results, which provide insights into the pore structure and surface area of the adsorbent materials, helps explain the observed differences in performance. The BET results from Figure 7 showed that the 85:15 composition had a larger average pore size compared to the 100:0 composition. Larger pores are beneficial in adsorption processes as they allow more seawater to interact with the adsorbent surfaces, facilitating better ion exchange and removal of dissolved salts. This explains why the 85:15 composition outperforms the 100:0 composition in salinity reduction. The increased effectiveness of the 85:15 composition can also be attributed to the synergistic effects of combining zeolite and activated carbon. While zeolite provides a structured framework and ion exchange capabilities, activated carbon contributes additional porosity and a high surface area, enhancing the overall adsorption capacity. This combination not only increases the efficiency of salt removal but also improves the kinetics of the adsorption process, allowing for faster and more effective salinity reduction. Thus, the analysis clearly shows that by optimizing the pore size through specific adsorbent compositions, the effectiveness of seawater desalination can be significantly enhanced.

Table 5 compares various adsorbent materials for desalination, including the natural zeolite composite developed in this study and those from prior research. Our natural zeolite and

Table 5. Comparison between Various Adsorbent Materials of Seawater in This Work and Previous Reported Works

Material	Parameters				Chemical Composition (mg/L)						Ref.
	Salinity (‰)	TDS (mg/L)	Hardness of Water (mg/L)	Electrical Conductivity (μS/cm)	Cl^-	Na^+	SO_4^{2-}	Mg^{2+}	Ca^{2+}	K^+	
Pahae Natural Zeolite -Activated Carbon Kepok Banana Peel	18.53	895.21	185.93	1,214	272.76	148.77	321.15	43.28	301.31	6.69	Present Work
Sukabumi Natural Zeolite	33.20	-	-	-	-	-	-	-	-	-	(Wajima, 2019)
Buah Batu Natural Zeolite	38.40	-	-	-	-	-	-	-	-	-	(Wibowo et al., 2015)
Koriyama Natural Zeolite	21.50	-	-	-	12,409	5,027	1,520	592.00	2,330	140.00	(Wibowo et al., 2017a)
Pahae Natural Zeolite-Polystyrene	-	-	-	202,000,000	-	-	-	-	-	-	(Sihombing et al., 2022)

activated carbon composite effectively reduce salinity to 18.53 ‰, with a TDS of 895.21 mg/L and hardness of 185.93 mg/L. Additionally, it lowers electrical conductivity to 1,214 μS/cm, with chloride (Cl^-) and sodium (Na^+) ions at 272.76 mg/L and 148.77 mg/L, respectively, outperforming other materials in ion reduction. Compared to other zeolites, such as the Buah Batu and Koriyama types, our composite demonstrates superior ion exchange capacity, especially for calcium and magnesium ions. Unlike these other materials, our composite functions independently, requiring no external chemical or thermal inputs. In summary, this zeolite-based adsorbent offers a sustainable, cost-effective desalination method, suitable for regions lacking energy-intensive infrastructure. Future studies will explore its adsorption capacity, regeneration potential, and scalability for larger desalination applications.

The desalination process employing adsorbents derived from Pahae natural zeolite and activated carbon is systematically depicted in Figure 8. This illustration elucidates the intrinsic mechanisms of salt and mineral adsorption from seawater. The pore sizes within the zeolite range from 49.26 to 84.67 Å, accommodating water molecules and both singly and doubly charged ions. However, only molecules and ions that are small enough to pass through these pores are allowed entry, thereby imparting a "molecular sieving" characteristic to the zeolite. In addition, the adsorptive capabilities of activated carbon enhance the process. The integration of these materials facilitates the efficient removal of various dissolved salts and minerals by exploiting the distinct characteristics inherent to each adsorbent. Pahae natural zeolite functions predominantly as a molecular siever, filtering appropriate molecular size that unfit into the pores, notably sodium (Na^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) ions. Its structural composition, characterized by a network of uniformly sized pores and channels, enables the selective absorption of these cations. During the desalination process, the cations within seawater are preferentially exchanged for the native cations present within the zeolite framework. This exchange is facilitated by the zeolite's negatively charged alumino- silicate framework, which attracts the positively charged ions from the seawater. The process is highly selective, ensuring that only ions that can be accommodated by the pore sizes are retained. This specificity largely depends on the ionic radius and charge density of the ions, contributing to the zeolite's efficiency in reducing water hardness and overall salinity.

Furthermore, activated carbon plays a crucial role in the removal of organic compounds and larger inorganic molecules. Its extensive internal surface area, formed by an intricate network of micro, meso, and macropores, provides substantial sites for the adsorption of these larger molecules through van der Waals forces and other non-covalent interactions. This physical adsorption process complements the ion exchange properties of the zeolite by capturing non-ionic and larger molecular contaminants that are not affected by the zeolite's sieving capabilities. The simultaneous utilization of these adsorbents in the desalination process ensures a comprehensive approach to purifying seawater. As water passes through layers of zeolite and activated carbon, a sequential filtration mechanism takes place. Initially, the zeolite selectively filters out specific ions based on size and charge, while subsequent layers of activated carbon trap organic and larger inorganic molecules, ensuring that the resulting water is not only less saline but also substantially free of a wide range of contaminants. This integrated adsorptive approach, therefore, represents a promising advancement in sustainable desalination technology, offering an effective solution for producing potable water from seawater while addressing environmental and economic concerns associated with conventional desalination practices.

4. CONCLUSIONS

The study examined a novel composite of Pahae natural zeolite and activated carbon from Kepok banana peels for seawater desalination. Through material characterization and performance testing, the optimal ratio was found to be 85:15 (zeolite to activated carbon), which provided the highest porosity (61.04%) and water absorption (86.65%). This composition effectively reduced salinity from 27.70‰ to 18.53‰, achieving a 33.10% salinity removal efficiency, and lowered TDS from 17,190 mg/L to 895.21 mg/L. It also reduced chloride and sodium concentrations to 272.76 mg/L and 148.77 mg/L, respectively. SEM analysis showed that increased porosity improved adsorption, while FTIR and XRD indicated enhanced ion exchange and a structural shift from crystalline to amorphous. These results suggest that the 85:15 zeolite-activated carbon composite could be a cost-effective, eco-friendly solution for seawater desalination, with potential for future optimization and scalability in water purification applications

5. ACKNOWLEDGMENT

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