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Peat Water Purification using Pahae Natural Zeolite and Activated Carbon Derived from Candlenut Shell (*Aleurites moluccana*)

(Pembersihan Air Gambut menggunakan Zeolit Semula Jadi Pahae dan Karbon Teraktif Diperoleh daripada Tempurung Kemiri (*Aleurites moluccana*))

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ABSTRACT

The escalating demand for freshwater due to the increased global population and intensified industrial activities necessitates innovative approaches to water treatment. This study explores the efficacy of a novel composite adsorbent material consisting of Pahae natural zeolite and activated carbon derived from candlenut shells for purifying peat water. This research synthesizes and evaluates the composite under varying conditions to determine its potential as an effective adsorbent material. Characterization methods included X-ray fluorescence (XRF), scanning electron microscopy (SEM), energy dispersive X-ray (EDX), X-ray diffraction (XRD), Fourier Transform Infrared (FTIR), Brunauer-Emmett-Teller (BET) and physical properties of adsorbent. The results demonstrated that the 80:20% zeolite to activated carbon ratio exhibited the highest porosity of 56.49% and a significant water absorption capacity of 53.65%. This composition also achieved the most peat water substantial purification lowering the initial turbidity, pH, color, iron and manganese concentration from 175.4 TCU, 31.32 NTU, pH 5, 1.44 mg/L, and 0.76 mg/L to 41.7 TCU, 11.24 NTU, pH 6.8, 0.242 mg/L, and 0.020 mg/L. SEM analyses showed a more porous surface morphology at 80:20% which corroborated with the higher purification of peat water. The adsorption mechanisms involving physical adsorption due to pore size were integral as the adsorbent in capturing contaminants. The findings suggest that such adsorbent can be tailored to improve performance and provide a viable solution to the global freshwater scarcity challenge.

Keywords: Activated carbon; adsorbent; natural zeolite; peat water; water treatment

ABSTRAK

Permintaan air tawar yang semakin meningkat berikutan pertambahan penduduk global dan aktiviti perindustrian yang semakin giat memerlukan pendekatan inovatif untuk rawatan air. Penyelidikan ini mengkaji keberkesanan bahan penjerap komposit baharu yang terdiri daripada zeolit asli Pahae dan karbon teraktif yang diperoleh daripada cengkerang kemiri untuk menulenkan air gambut. Penyelidikan ini mensintesis dan menilai komposit dalam keadaan yang berbeza-beza untuk menentukan potensinya sebagai bahan penjerap yang berkesan. Kaedah pencirian termasuk pendarfluor sinar-X (XRF), mikroskop elektron pengimbasan (SEM), tenaga penyerakan sinar-X (EDX), pembelauan sinar-X (XRD), transformasi Fourier inframerah (FTIR), Brunauer-Emmett-Teller (BET) dan sifat fizikal penjerap. Keputusan menunjukkan bahawa nisbah 80:20% zeolit kepada karbon teraktif menunjukkan keliangan tertinggi sebanyak 56.49% dan kapasiti penyerapan air yang ketara sebanyak 53.65%. Komposisi ini juga mencapai penulenan besar air gambut yang paling banyak dengan merendahkan kekeruhan awal, pH, warna, besi dan kepekatan mangan daripada 175.4 TCU, 31.32 NTU, pH 5, 1.44 mg/L dan 0.76 mg/L kepada 41.7 TCU, 11.24 NTU, pH 6.8, 0.242 mg/L dan 0.020 mg/L. Analisis SEM menunjukkan morfologi permukaan yang lebih berliang pada 80:20% yang disokong dengan penulenan air gambut yang lebih tinggi. Mekanisme penjerapan yang melibatkan penjerapan fizikal disebabkan saiz liang adalah penting sebagai penjerap dalam menangkap bahan cemar. Keputusan menunjukkan bahawa penjerap tersebut boleh disesuaikan untuk meningkatkan prestasi dan menyediakan penyelesaian yang berdaya maju kepada cabaran kekurangan air tawar global.

Kata kunci: Air gambut; karbon teraktif; penjerap; rawatan air; zeolit asli

INTRODUCTION

The challenge of securing clean water for populations residing in peatlands remains critical. Globally, peatlands cover an estimated 4.23 million square kilometers, accounting for about 2.84% of the Earth's total land surface (Xu et al. 2018). Anda et al. (2021) conducted a comprehensive survey of peatland regions in Indonesia, showing that these areas encompass 13.43 million hectares, distributed across four principal islands in descending order of size: Sumatra (5.85 million hectares), Kalimantan (4.54 million hectares), Papua (3.01 million hectares), and Sulawesi (0.024 million hectares). In several Indonesian regions, peat water is the primary source of surface water (Ali, Lestari & Putri 2021). This water typically exhibits a reddish-brown hue, has a pH ranging from 3 to 5, and contains high levels of organic substances, such as humic and fulvic acids. The nature of peat water in these regions necessitates advanced treatment technologies to make it safe for consumption; hence, the task of providing potable water in these areas is formidable due to the intrinsic properties of peat water, which are associated with numerous health risks.

The issue is particularly acute in peatland areas, where the consumption of untreated peat water poses severe health threats. Research indicates that peat water from swamp forests can vary significantly in acidity and organic content, influenced by regional vegetation and environmental factors (Syafalni et al. 2013). In their natural state, tropical peatlands act as freshwater reserves, stabilize water levels, diminish peak storm flows, sustain river flow during dry periods, and protect against saltwater encroachment (Wösten et al. 2008). The presence of high acidity and organic material necessitates specific treatment processes before peat water can be utilized as a water source. Therefore, it is crucial to secure and possibly expand local water sources, including exploring new options like peat swamp forests, to mitigate potential future water scarcities.

Various methods have been implemented for treating peat water, including traditional processes like coagulation (Abdul Rahman et al. 2023), oxidation (Qadafi, Notodarmojo & Zevi 2020), adsorption (Wenten et al. 2020), and membrane filtration (Nasir et al. 2024). Traditional treatments have effectively reduced the color and organic material in peat water, transforming it into water that is safe for consumption. Nonetheless, the accessibility of necessary equipment poses economic and technological challenges for inhabitants of peatland regions. Among the various technologies proposed for purification, those utilizing adsorption techniques with sorbent materials have garnered significant attention due to their environmentally friendly nature, low operational costs, and minimal ecological footprint (Fatimah et al. 2023; Utama et al. 2020). This method 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 reduction of iron and manganese ions, thereby enhancing its quality for intended uses (Fatimah et al. 2023; Utama et al. 2020).

Zeolite, an inorganic mineral, has received considerable attention both in Indonesia and internationally for its outstanding adsorption properties (de Magalhães et al. 2022; Luo et al. 2021; Sihombing et al. 2022; Xiao et al. 2024). This interest stems largely from its porous structure and excellent physicochemical characteristics (Nasution et al. 2015; Sudibandriyo & Putri 2020; Susilawati et al. 2023, 2022, 2018). Zeolite features a high cation exchange capacity, a selectivity for specific cations, and a significant pore volume (Susilawati et al. 2021, 2017; Wibowo et al. 2017). Its amorphous framework, composed of interconnected cavities, enables the effective adsorption of small molecules over a large surface area (Calabrese 2019; Khaleque et al. 2020; Zarrintaj, Mahmodi & Manouchehri 2020). In the specific context of peat water purification, zeolite's cation exchange properties play a crucial role. Zeolite's ability to selectively adsorb and exchange these cations makes it particularly effective for such applications. The ion-exchange process involves the substitution of native cations in the zeolite with contaminant cations from the water, such as heavy metals. This exchange is facilitated by the zeolite's negatively charged alumino-silicate framework, which attracts positively charged contaminants, effectively removing them from the water. The capability of zeolite to absorb cations, aiding in catalytic exchanges, is fundamental to its application in various fields, including water filtration and humidity control. In the realm of water remediation, natural zeolites stand out as superior sorbents due to their hydration properties and exceptional ion-exchange capabilities, facilitating the efficient elimination of heavy metal ions from aquatic environments. When compared to other economical adsorptive materials such as activated carbon, fly ash, and clay, natural zeolites demonstrate enhanced performance (Calabrese 2019; de Magalhães et al. 2022). Their non-toxicity, abundance, and cost-effectiveness render them highly favored for environmental uses, such as water purification, wastewater management, and the treatment of polluted waters (de Magalhães et al. 2022).

There is evidence that natural zeolite as adsorbents can effectively remove organic matter, heavy metals, dyes and phenolic compounds. A cationic surfactant modified zeolite with granular activated carbon and limestone exhibits pH = 7.78, color = 12 TCU, turbidity = 0.23 NTU, COD= 0 mg/L and Fe = 0.11 mg/L (Syafalni et al. 2013). Although research demonstrates the impressive capabilities of natural zeolites for adsorption, it also underscores the obstacles in attaining enhanced efficiency and uniform outcomes. These challenges could be addressed by further refining the process, possibly through the addition of supplementary materials that boost the adsorption performance of natural zeolites in diverse environmental settings.

The shell of the candlenut (*Aleurites moluccana*), a byproduct from processing the fruit for agricultural use, represents a significant source of agro-industrial waste. According to Patabang, Siang and Basri (2021), Indonesia produces approximately 100,700 metric tons of candlenut annually. Global statistics from the Food and Agriculture Organization (FAO) indicate that in 2020, worldwide candlenut production amounted to 554,490 metric tons. With the shells constituting about 66.1% of this product, it is estimated that around 366,518 metric tons of solid biowaste are generated each year from this industry (Martín et al. 2010). Harnessing this substantial waste for adsorption technology could prove immensely beneficial for candlenut producers. By converting candlenut shells into biosorbents, farmers can not only generate additional income but also alleviate environmental stress. This conversion process could significantly cut down agricultural waste and aid in environmental conservation by stabilizing carbon in a solid form (Alfatah et al. 2022). Consequently, this would reduce the emissions of gases such as CH_4, CO, and CO_2, which are linked to climate change, rising global temperatures, and deteriorating air quality (Mariana et al. 2021; Mistar et al. 2018).

The adsorptive efficiency of zeolite can be significantly improved by combining it with materials known for their high adsorption capabilities. Activated carbon, with its extensive surface area and porous nature, is particularly effective at removing a variety of pollutants (Saad et al. 2020a, 2020b). Integrating zeolite with activated carbon could synergistically enhance the properties of both, optimizing the purification process for peat water. Specifically, activated carbon made from candlenut shells, a common agricultural byproduct in Indonesia, is an excellent choice for such applications. The carbonaceous material and active groups within the candlenut shells facilitate bio adsorption. Recent studies have shown that activated carbon derived from candlenut shells effectively adsorbs methylene orange dyes (Muliani, Zakir & Fauziah 2023), mercury(II) (Mariana et al. 2022) and seawater desalination (Anas et al. 2024). Building on these results, this study explores the use of natural zeolite from Pahae combined with activated carbon from candlenut shells to purify peat water. The properties of these sorbent mixtures, such as porosity, hardness, and water absorption capacity, were evaluated. Advanced characterization techniques, including X-ray fluorescence (XRF), Scanning Electron Microscopy (SEM), Energy Dispersive X-ray (EDX), and X-ray Diffraction (XRD) were utilized to explore the potential of this composite material as an effective purifier. These analyses shed light on the structural and functional characteristics that enhance the adsorption efficacy of the combined sorbent materials.

MATERIALS AND METHODS

MATERIALS

In this research, materials were locally sourced from North Sumatra, Indonesia, to harness the combined benefits of Pahae natural zeolite and candlenut shells for peat water purification. Specifically, natural zeolite was obtained from the Pahae District in North Tapanuli Regency, while candlenut shells and peat water were gathered from Sidikalang in Dairi District, showcasing the diverse natural resources of the region. The use of local peat water as the primary material for purification was directed towards alleviating the region’s freshwater shortages. Moreover, the choice of local adsorbent materials underlines a commitment to utilizing regional resources to effectively address economic development challenges.

SYNTHESIS OF PAHAE NATURAL ZEOLITE-CANDLENUT SHELLS ACTIVATED CARBON AS ADSORBENT MATERIAL

Natural zeolite obtained from the Pahae District in North Tapanuli, North Sumatra, was initially processed by manually crushing and grinding it using a mortar and pestle to diminish its coarse form. This ground zeolite was then passed through a 200-mesh sieve to ensure consistent particle size. After sieving, the zeolite was repeatedly washed in distilled water three times and subsequently dried in an oven at 100 °C for a duration of 24 h. It underwent a second drying phase under the same conditions to enhance its adsorption capabilities. A chemical activation process was then applied to the zeolite that had been prepared mechanically; it was soaked in a 10% w/v solution of KOH and stirred continuously at 135 rpm while being maintained at 60 °C for 1 h. After this chemical treatment, the zeolite was again dried in the oven to achieve optimal activation. Separately, candlenut shells sourced from Sidikalang in Dairi District were processed by removing any remaining seeds and flesh, cutting them into smaller fragments, and drying them at 100 °C for 7 h in an oven. These dried shells were then carbonized at 300 °C for 2 h in a furnace to create activated carbon, which was subsequently ground and passed through a 200-mesh sieve.

The processed Pahae natural zeolite and activated carbon from candlenut shells were combined in various weight ratios: 100:0%, 95:5%, 90:10%, 85:15%, 80:20%, 75:25% and 0:100%. These mixtures were then subjected to agitation in a YM1832 Yami shaker for 5 min. Following this, distilled water amounting to 50% v/w of the total mixture was added, and the mixture was agitated again. Each blend was then molded into blocks measuring $3 \times 3 \times 1$ cm^3 using a Hydraulic Press Ytd27-200t, applying a pressure of 6 tons for 10 min. This procedure was performed for each blend ratio. After air-drying for one week, the samples underwent sintering at 600 °C for 2 h to minimize cracking during the physical activation phase.

This research presents an innovative adsorbent comprising natural zeolite and activated carbon derived from candlenut shells, a blend not previously documented in academic studies. The study investigates the effectiveness of this composite material in purifying peat water, a subject that has received limited attention. This novel method utilizes the adsorptive qualities of both natural zeolite and carbonized candlenut shells to tackle the issue of freshwater scarcity. The research underscores the viability of using locally sourced, eco-friendly materials for purification purposes, thereby advancing the development of economical and efficient water purification solutions.

CHARACTERIZATIONS

The characterization of the developed adsorbent materials, composed of Pahae natural zeolite and activated carbon derived from candlenut shells, was conducted using a multifaceted analytical approach. Prior to blending process, Pahae natural zeolite was characterized using X-Ray Fluorescence (XRF) PANalytical Epsilon 3 before and after activation. The materials were examined with a JEOL JSM6390 scanning electron microscope (SEM) and an Oxford Instruments energy-dispersive X-ray (EDX) analyzer to determine key features such as morphology and elemental composition. A Philips PW 1050 X-ray diffractometer (XRD) was used to analyze the crystalline phases in the samples over a wavenumber range, scanning 2θ angles from 7 to 70°. Fourier Transform Infrared (FTIR) measurements were performed using a PerkinElmer System IR 2000 spectrometer, which operated over a wavenumber spectrum of 4,000 to 400 cm^{-1}, employing the KBr pellet method for 100 scans. The surface area of the specimens was determined through the Brunauer-Emmett-Teller (BET) approach, utilizing a relative pressure interval of 0.05 to 0.2. Measurements of total pore volumes and their distribution were conducted at a relative pressure of $P/P_0 = 0.99$, using nitrogen adsorption isotherm data and the Non-Local Density Functional Theory (NLDFT) method. The average pore size was derived using the equation 4 V/A, where V represents the pore volume and A denotes the surface area. This comprehensive set of analytical tools provided a detailed understanding of the physical and chemical properties of the adsorbent material, which was crucial for evaluating its efficacy in peat water purification.

PEAT WATER PURIFICATION METHOD

Initial evaluation tests were conducted to assess the physical characteristics of the adsorbent materials, specifically Pahae natural zeolite and activated carbon made from candlenut shells, in varying compositions. These tests measured the porosity, water absorption capacity, and hardness of each composite. Porosity, a crucial parameter for evaluating adsorbent efficiency, was determined using Equation (1), which calculates the volume fraction of void spaces within the sample as follows:

$$\%\, porosity = \left(\frac{m_w - m_d}{\rho_w \times V_t}\right) \times 100\% \quad (1)$$

where m_w represents the wet mass in grams; m_d the dry mass in grams; ρ_w the density of water in grams per cubic meter; and V_t the volume of the sample post-combustion in cubic meters. Water absorption capacity was assessed using Equation (2), by comparing the mass of the samples before and after immersing them in water for 24 h at room temperature. This immersion tests the adsorbent material's capacity to retain water, as detailed herewith:

$$\%\, water\ absorption\ test = \left(\frac{m_w - m_d}{m_d}\right) \times 100\% \quad (2)$$

where m_w denotes the wet mass in grams; and m_d the dry mass in grams. The hardness of the composites was determined using the Hardness tester YD-3, which assesses the material's resistance to physical deformation when subjected to pressure. 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 purification.

Before purification process, the peat water was collected and analyzed to determine its color, turbidity and pH were measured in line with Class 1 of the national raw water standards set by the Government of Indonesia regulation No. 22/2021. The American Public Health Association (APHA) established a standard method for water and wastewater analysis, which we used to analyze the water parameters. In this study, the concentration of Iron and Mangan was determined using Agilent ICP EOS Spectrometer, following APHA 3120B. After that initial characterization, the adsorbent materials comprised of activated Pahae natural zeolite and activated carbon from candlenut shells, were immersed in peat water within transparent bottles. It was then submitted to mechanical shaking to facilitate the adsorption process of materials. This methodological approach helps in the evaluation of peat water purification from the adsorbent materials together with the possibility of optimization of purification for practical applications.

RESULTS AND DISCUSSION

XRF ANALYSIS

XRF testing was conducted to determine the elemental content in Pahae natural zeolite before and after activation with a 10% KOH solution. Based on the XRF analysis results shown in Table 1, the content of Si (silica) in Pahae natural zeolite before activation with 10% KOH was 32.538%, and after activation with 10% KOH, it increased to 44.161%. The chemical activation treatment on natural zeolite was able to increase the purity of the zeolite and remove impurities from the natural zeolite. The most dominant elements in the zeolite are Si and Al, with a Si/Al ratio of 3.9 before activation and 5.6 after activation. Thus, Pahae natural zeolite included into the category of zeolites with a medium Si/Al ratio. The type of natural zeolite formed is mordenite. Mordenite Pahae natural zeolite has a Si/Al ratio ranging from 4.17 to 10. The application of a KOH solution to the Pahae natural zeolite serves a critical function in the activation process. KOH is specifically used for its strong basic properties, which facilitate the dissolution of metal oxides that coat and are absorbed into the surface of the zeolite. This action significantly enlarges and enhances the porosity of the contact surface, making it more effective for adsorption processes (de Magalhães et al. 2022; Susilawati et al. 2022). Moreover, the chemical activation with bases like KOH not only purifies the pores by removing impurity compounds but also aids in rearranging the atomic structure of the exchanged elements. This rearrangement and cleaning of the zeolite's pores are essential for enhancing the zeolite's specific properties and removing the impurity elements embedded within the Pahae natural zeolite. Such modifications are crucial for optimizing the zeolite's performance in various applications, including filtration and adsorption.

MORPHOLOGICAL ANALYSIS

Scanning Electron Microscopy (SEM) was employed to examine the surface morphology of composite adsorbents made from Pahae natural zeolite and activated carbon obtained from candlenut shells. Figure 1(a)-1(f) illustrates the morphological features of these composites, which vary in composition from 100:0%, 95:5%, 90:10%, 85:15%, 80:20% to 0:100%. The SEM images distinctly show a morphological transformation as the percentage of activated carbon increases. Figure 1(a), which shows the sample with 100% Pahae natural zeolite, displays a smooth and mostly uniform surface interspersed with minor fissures, characteristic of crystalline zeolitic structures. This pattern is marked by limited porosity and fewer pore

TABLE 1. Chemical composition (%) of Pahae natural Zeolite before and after activation

Element	% Weight	
	Before activation	After activation
Si	32.54	44.16
Al	8.26	7.94
Fe	19.09	7.18
K	18.41	20.17
Ca	13.78	12.76
Ti	2.49	1.91
P	2.52	2.86
Mn	0.26	0.18

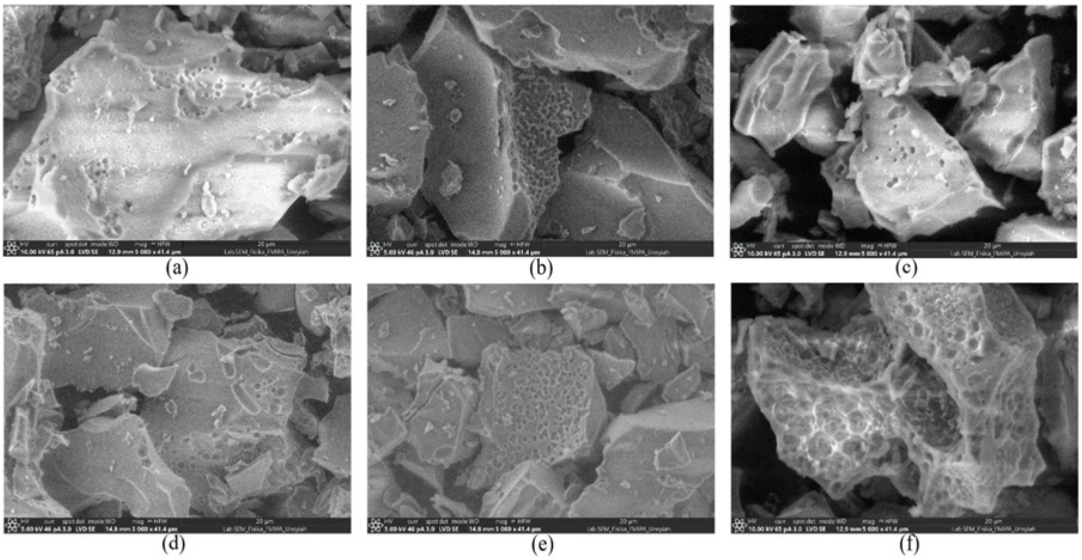

(a) (b) (c)
(d) (e) (f)

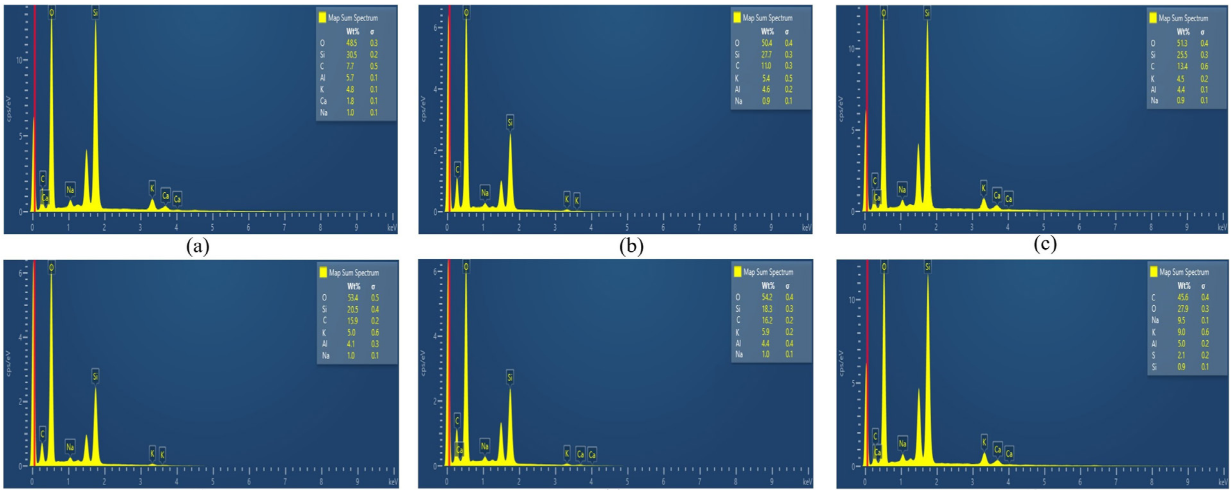
FIGURE 1. SEM images of adsorbent made from Pahae natural zeolite and activated carbon derived from candlenut shells with variation composition of (a) 100:0; (b) 95:5; (c) 90:10; (d) 85:15; (e) 80:20 and (f) 0:100

openings. Figure 1(b) to 1(e), which show a decreasing ratio of zeolite from 95% to 80% and an increasing amount of activated carbon, demonstrate a consistent increase in both surface roughness and porosity. This transformation is characterized by more visible pores and a textured appearance. These modifications are due to the porous characteristics of the activated carbon, sourced from candlenut shells, which interrupt the compact zeolitic framework, thus expanding the surface area and potentially improving the adsorptive capabilities (Anas et al. 2024; Saad et al. 2020a, 2020b).

Intriguingly, Figure 1(f), displaying the 0:100% activated carbon configuration, shows a notably more compact and denser surface compared to the mixtures of 90:10%, 85:15%, and 80:20%. This pattern indicates that at full concentration, activated carbon tends to adopt a more tightly packed structure, potentially leading to reduced porosity. This densification may be attributed to the thermal treatment at 600 °C, which is likely to alter the carbon's structural properties, resulting in fewer pores (Mariana et al. 2022). These morphological findings are vital for adsorption processes, as increased porosity and surface area are directly linked to the adsorbents' capacity to absorb and hold chemical entities (Li et al. 2024; Shoumkova & Stoyanova 2013). Consequently, the morphological analysis supports the notion that blending activated carbon with Pahae natural zeolite improves the composite's adsorptive qualities, with higher ratios of activated carbon enhancing surface area and porosity, key elements for boosting adsorption effectiveness. This implies that the adsorptive characteristics of the composite can be adjusted by modifying the zeolite-to-carbon ratio, providing a flexible approach for purification tasks.

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)-2(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), aluminium (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 30.5 wt% and O 48.5 wt%, reflecting the siliceous nature of the material. The presence of Al 5.7 wt% is also notable, which is characteristic of the aluminosilicate framework of zeolites. As the percentage of carbon (derived from candlenut shells) 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 of 11 wt% 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% i.e., 13.4, 15.9 and 16.2 wt% where the carbon content progressively dominates the spectra. By the 0:100% composition, where the adsorbent is purely derived from candlenut shells, the EDX spectrum is primarily characterized by carbon and oxygen i.e., 45.6 and 27.9 wt%, with minimal peaks of silicon 0.9 wt%. 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



(a) (b) (c)

(d) (e) (f)

FIGURE 2. EDX test results of adsorbent made from Pahae natural zeolite and activated carbon derived from candlenut shells with variation composition of (a) 100:0; (b) 95:5; (c) 90:10; (d) 85:15; (e) 80:20 and (f) 0:100

on the material’s surface (Kordala & Wyszkowski 2024). These findings highlight the significant impact of the compositional variation on the elemental content of the adsorbents, which in turn influence the capability in reduction of peat water purification.

XRD ANALYSIS

The compositional variations between pure zeolite and activated carbon derived from candlenut shell ranging from 100:0% to 0:100% were examined using X-ray Diffraction (XRD) to assess the crystalline and amorphous structures within these materials. As shown in Figure 3, notable changes in peak intensity and positioning indicate structural alterations in the adsorbents as the balance between zeolite and activated carbon shifts. In the pure zeolite sample (100:0), the pronounced peak intensities signify a predominantly crystalline structure is represented with peaks of 2θ = 28.04 and 2θ = 29.85, which is crucial for the ion-exchange and adsorptive processes in purification, particularly adept at capturing specific ions from peat water. For the 95:5 sample, the peaks are still identifiable at 2θ = 28.01° and 2θ = 29.82°, while 90:10 composition the peaks shift slightly to 2θ = 28.00° and 2θ = 29.80° suggesting increased integration of activated carbon, which dilutes the crystalline order of the zeolite. At the 85:15 ratio, the peaks appear at 2θ = 27.98° and 2θ = 29.78°, when the composition reaches 80:20, the peaks are faintly visible at 2θ = 27.95° and 2θ = 29.75°, indicating a predominant amorphous structure in the adsorbent mixture. In the pure activated carbon sample (0:100), the crystalline peaks are entirely absent, replaced by a broad hump centered around 2θ = 20°–30°, characteristic of amorphous carbon. This transformation to an amorphous structure enhances the adsorptive capacity by providing a larger surface area and more accessible pore spaces, making it effective for the adsorption of organic and metallic contaminants.

The amorphous nature of activated carbon allows the adsorption of molecules of various sizes and shapes, with the removal of a wide range of contaminants and high organic content in peat waters. However, this may reduce the precise selectivity that crystalline zeolite offers for specific ions. XRD data suggest that combining zeolite and activated carbon could merge the precise ion-selectivity of crystalline zeolite with the extensive adsorptive capacity of amorphous activated carbon. Selecting the right blend depends on the specific needs of the purification process, such as water purity, types of impurities, and operational efficiency. The insights gained from XRD analysis are crucial for customizing adsorbent materials to optimize purification performance, indicating that a strategic mix of crystalline and amorphous phases in adsorbents can effectively purified peat water and enhance the overall water quality.

FTIR ANALYSIS

FTIR analysis was utilized to identify the functional groups in adsorbent materials consisting of pure zeolite and activated carbon derived from candlenut shells, varying

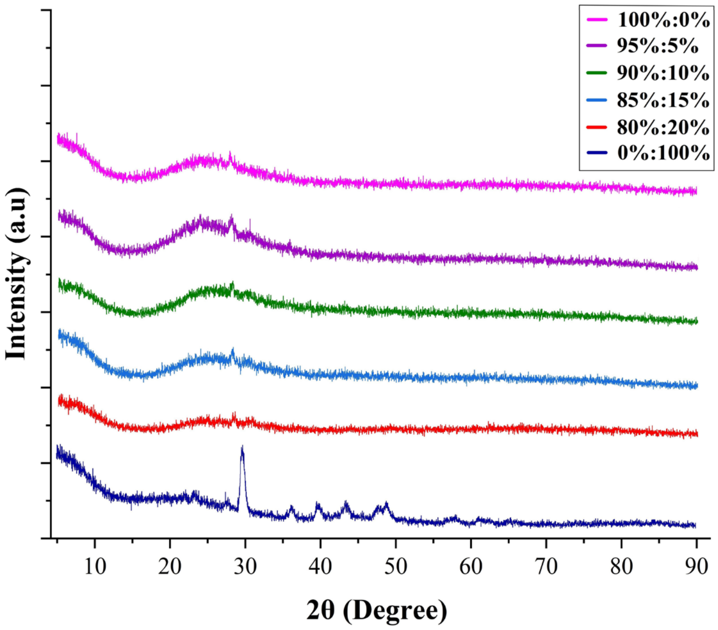


FIGURE 3. Diffraction pattern of adsorbent made from Pahae natural zeolite and activated carbon derived from candlenut shells with variation composition

in composition from 100% zeolite to 100% activated carbon. The FTIR spectra displayed in Figure 4 show clear variations in transmittance at different wavenumber intervals, providing insight into the chemical properties and potential adsorptive capabilities of the materials. The peaks in transmittance seen in the spectra correspond to specific functional groups important for the adsorption processes used in purification. Notably, the broad bands around 3,400 cm^{-1}, consistent across all samples, indicate O-H stretching vibrations characteristic of hydroxyl groups. These groups are crucial for interacting with water molecules, potentially improving the adsorption of water-soluble pollutants and ions commonly present in peat water.

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 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 purification, as it aids in the removal of heavy metal ions from peat waters. The overall effect of these functional groups, as shown by the FTIR analysis, on the purification 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 peat water. This tailored approach enables the creation of more efficient adsorbent materials that can address the diverse challenges posed by different impurities in peat water, thus improving the efficacy and efficiency of purification processes.

BET ANALYSIS

The Brunauer-Emmett-Teller (BET) analysis details the nitrogen adsorption-desorption isotherms and the average pore sizes of composite materials made from Pahae zeolite and activated carbon derived from candlenut shells. These

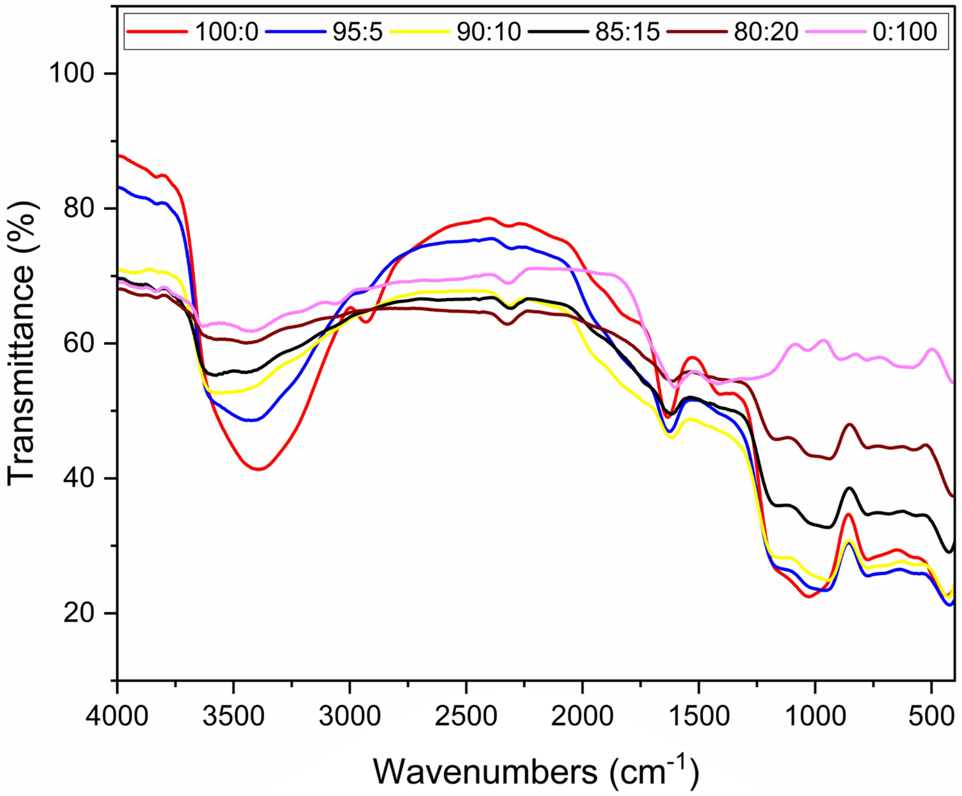


FIGURE 4. FTIR spectra adsorbent made from Pahae natural zeolite and activated carbon derived from candlenut shells with variation composition

composites' composition plays a pivotal role in determining their adsorptive efficiency. Table 2 displays the BET results for varying ratios ranging from 100:0% zeolite to activated carbon, to 0:100% activated carbon. The differences in pore size among these composites are crucial, influencing their performance in purification. Notably, the 80:20% zeolite to activated carbon ratio shows the highest average pore size at 63.08 Å, enhancing its effectiveness in purification due to the ability of larger pores to support more extensive ion exchange and adsorption activities, crucial for capturing and eliminating the wide variety of salts and minerals in peat water. This larger pore structure likely enhances water throughput, increasing the efficiency of salt removal. In contrast, the 100:0% composition, solely comprising Pahae zeolite, has a considerably smaller average pore size of 16.29 Å, which restricts the interaction volume and rate of peat water with the adsorbent's active sites, thus diminishing its capacity for efficient salt ion adsorption and removal. Additionally, the specific surface areas and total pore volumes of these composites show significant variation correlating with changes in their compositional ratios. The sample with 80:20% zeolite to activated carbon ratio exhibits the largest specific surface area (29.07 m²/g) and total pore volume (0.02861 cm³/g), indicating a high availability of adsorptive sites and significant porosity beneficial for adsorption processes. The increase in surface area and pore volume, correlated with a higher percentage of activated carbon, aligns with activated carbon's characteristic of possessing a more expansive pore network compared to zeolite.

The external surface area (SExt) and micropore volume (VMicro) are key indicators of the textural properties of these composites. The data indicates an upward trend in both SExt and VMicro with an increase in the percentage of activated carbon in the mix. For example, the composite with an 80:20% zeolite to activated carbon ratio exhibits a larger external surface area (29.07 m²/g) than the purely zeolite composition (11.83 m²/g), underscoring the role of activated carbon in enhancing the accessibility of external surfaces, which is advantageous for the adsorption of larger molecular species. These material characteristics are vital in practical scenarios, such as purification, where the dynamics of adsorption and the efficacy of ion exchange are pivotal.

The pattern observed where larger average pore diameters (DPore), exemplified by the 63.08 Å in the 80:20% composite, indicates that these materials are highly effective for targeting larger molecular structures commonly present in brackish and peat water. This characteristic renders them particularly advantageous not only for conventional adsorption uses but also for more stringent environmental applications, such as removing heavy metals and larger organic contaminants that necessitate access to broader pore structures. This outcome underscores the limitations of using solely zeolite in situations where greater adsorptive capacities and quicker filtration speeds are necessary, as may be required in industrial-scale purification operations. The findings suggest that blending activated carbon with zeolite significantly augments the composite's structural attributes, like pore size, thereby enhancing its functional performance in purification.

The BET analysis displayed in Figure 5 meticulously examines the nitrogen adsorption-desorption isotherms for composites of Pahae zeolite and activated carbon sourced from candlenut shells, across a range from 100:0% to 0:100%. Figure 5 illustrates that the amount of nitrogen adsorbed escalates as the relative pressure P/P_0 increases, with all samples exhibiting Type IV isotherms indicative of mesoporous structures. Such isotherms generally signify capillary condensation within mesoporous frameworks and are accompanied by hysteresis loops, which point to irregularities and interconnectivity within the pore networks. Notably, the data reflects the impact of increasing activated carbon content on enhancing adsorption capacities, especially evident as the activated carbon ratio reaches 20%, where an increase in adsorption capacity at higher relative pressures becomes apparent. This enhancement is attributed to the inherent high porosity of activated carbon, which boosts the composite's capability to adsorb larger gas volumes.

TABLE 2. Brunauer–Emmett–Teller (BET) result

Pahae zeolite : Activated carbon of candlenut shells	Average Pore Size [Å]	S_{BET} [m²/g]	S_{Ext} [m²/g]	V_{Total} [cm³/g]	D_{Pore} [Å]
100 : 0	16.29	11.83	2.55	0.00964	16.29
95 : 5	23.89	12.51	7.05	0.01494	23.89
90 : 10	35.19	15.32	10.54	0.01931	25.19
85 : 15	49.79	21.74	21.74	0.03239	29.79
80 : 20	63.08	29.07	29.07	0.02861	63.08
0 : 100	39.64	17.32	19.11	0.02109	26.24

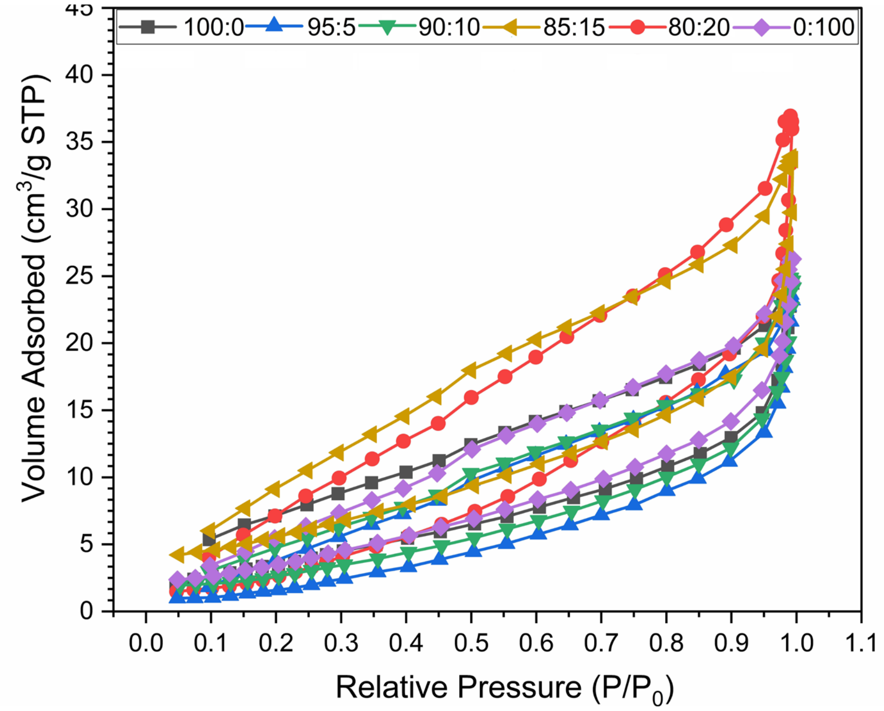


FIGURE 5. N_2 Adsorption-desorption Isotherm from Pahae natural zeolite and activated carbon derived from candlenut shells with variation composition

The compositions with a higher activated carbon content, such as the 80:20% ratio, the adsorption volume exhibits a sharper increase as it approaches saturation (P/P₀ nearing 1), suggesting larger or more widely distributed pore sizes that can accommodate increased gas molecules at elevated pressures. Conversely, the pure zeolite composition (100:0%) displays a comparatively lower adsorption capacity at all relative pressures, emphasizing the activated carbon's microporous structure's role in augmenting gas adsorption under the given experimental conditions. These observations delineate how composite makeup influences adsorption characteristics, with the addition of activated carbon significantly boosting the porosity and adsorption capacities of the materials, aligning with requirements for more effective purification processes that handle the high organic content in peat water.

PHYSICAL PROPERTIES OF ADSORBENT MATERIALS

A pre-evaluation was conducted to assess the physical properties of adsorbent materials -specifically Pahae natural zeolite and activated carbon derived from candlenut shells - in varying compositions. These preliminary tests focused on determining the porosity, water absorption capacity and hardness of each composite which depicted in Figure 6(a)-6(c)), respectively.

This thorough analysis establishes a clear understanding of the unique properties of each material, showing how their structural features could potentially enhance their performance in purification processes. Porosity is defined as the ratio of the volume of voids to the total volume and is calculated based on the mass difference between the sample's wet and dry states, which is then related to the water's density and volume. Porosity is a critical parameter as it directly impacts the adsorption efficiency of these materials. Figure 6(a) displays the porosity levels for various blends ranging from 100:0% to 0:100%. The data presented in this graph illustrates the impact of the adsorbents' structural attributes on their purification efficacy. Notably, the 80:20% zeolite to activated carbon mixture shows the highest porosity at 56.49%. Such elevated porosity indicates a larger volume of void spaces within the adsorbent, which increases the surface area accessible for the adsorption of ions from peat water (Vasconcelos et al. 2023). This enhanced porosity allows for more extensive interaction between the adsorbent and peat water, facilitating more effective extraction and removal. This is why the 80:20% composition is identified as the most efficient for purification.

Conversely, the 0:100% mixture, composed entirely of candlenut shells, exhibits a significantly reduced porosity of around 41.10%. This limited porosity reduces the volume of void spaces available for water interaction, thereby hindering the material's capacity for efficient adsorption. The performance of this composition in purification processes is constrained by these factors, as the lesser void spaces result in a decreased contact area between the adsorbent and the water, leading to less effective purification. The porosity trends clearly indicate that integrating activated carbon with the zeolite structure markedly increases the porosity of the adsorbent materials. Enhanced porosity not only facilitates better purification but could also accelerate the kinetics of the adsorption process, allowing more water to flow through the porous structure and increasing ion contact with adsorptive sites (Susilawati et al. 2022). Therefore, fine-tuning the porosity of adsorbent materials by modifying their composite ratios is essential for advancing more effective purification technologies.

Figure 6(b) demonstrates the water absorption capacities of adsorbent materials ranging from 100:0%, 95:5%, 90:10%, 85:15%, 80:20% to 0:100%. The outcomes from the water absorption tests shed light on the operational capabilities of different adsorbent compositions, especially their impact on purification efficiency. Notably, the 80:20% composition achieves the highest water absorption, which strongly aligns with superior purification results. Conversely, the 0:100% blend, solely comprising activated carbon derived from candlenut shells, shows the least capacity for water absorption. This low absorption is primarily attributed to the amorphous structure of the activated carbon affecting the features of pore sizes become smaller than the mixture of zeolite and activated carbon (Saad et al. 2020a, 2020b). Such limited pores restrict the material's ability to take in water, thus diminishing its purification effectiveness where water permeability and ion exchange are paramount. This reduced ability to absorb water leads to less interaction between the water and the adsorbent's surface, which in turn impairs the material's capacity to effectively extract organic compound from peat water.

In contrast, the 80:20% blend, integrating a substantial amount of activated carbon with zeolite, significantly enhances water absorption. This improvement stems from the activated carbon's inherent porous structure and extensive surface area, resulting in larger and more open pores (Susilawati et al. 2022). The increased porosity not only boosts the material's water absorption but also expands the contact area necessary for ion exchange and adsorption. This expanded interaction surface is vital for efficiently removing the diverse minerals present in peat water, making the 80:20% mixture particularly adept for purification tasks.

Results from the hardness tests on various adsorbent compositions, as shown in Figure 6(c), shows hardness values for mixtures ranging from 100:0% to 0:100%. The graph clearly illustrates the relationship between the hardness of the adsorbent materials and their purification performance. Specifically, the 100:0% zeolite composition, despite its higher hardness, proved less effective for purification compared to the 80:20% composition, which, with its slightly lower hardness, was the most effective.

The increased hardness observed in the 100:0% composition, primarily consisting of Pahae natural zeolite, indicates a denser and more compact crystalline structure. While such a structure typically offers durability and resistance to mechanical stress, it also tends to have smaller, less accessible pores. These restricted pore sizes hinder the flow of water and interaction with adsorptive sites, which are vital for effective ion exchange and organic compound removal in purification (Nasir et al. 2024; Syafalni et al. 2013). Therefore, despite its robust structure, the reduced pore accessibility in the pure zeolite composition limits its utility in water treatment applications (Susilawati et al. 2022). On the other hand, the 80:20% composition, which incorporates a significant amount of activated carbon, strikes a balance between hardness, pores and water absorption properties. Although the hardness is slightly reduced from pure zeolite, the addition of activated carbon improves the pore structure, creating larger and more accessible pores. This enhanced porosity allows for increased water flow and more extensive interaction with adsorptive sites, markedly boosting the efficiency of organic compound and minerals removal from peat water. The more open pores in this composition not only trap ions physically but also accelerate the adsorption kinetics, rendering it more effective for purification tasks.

PEAT WATER PURIFICATION ANALYSIS

Table 3 outlines the characteristics of raw peat water. In accordance with the Government of the Republic of Indonesia Regulation No. 22/2021, we evaluated peat water based on parameters such as turbidity, color, iron (Fe), manganese (Mn), and pH. This regulation does not require tests for acidity and color. According to Table 3, the raw peat water exhibits a turbidity of 31.32 NTU, a color value of 175.4 TCU, iron, and manganese concentrations of ≤0.3 mg/L and 0.4 mg/L, respectively, and a pH of 5. These indicators render the peat water unsuitable for direct consumption, necessitating purification processes.

Figure 7(a) illustrates the turbidity levels of peat water treated with various ratios of natural Pahae zeolite and activated carbon derived from candlenut shells. Turbidity, measured in Nephelometric Turbidity Units (NTU), is a key parameter indicating the clarity of water, with lower values signifying clearer water. The graph shows that as the percentage of activated carbon increases, turbidity levels approach and even fall below the acceptable standard of ≤ 25.00 NTU, highlighted by the dashed red line. The initial turbidity of the raw peat water was 31.32 NTU and subsequently decreased to the lowest value of 11.24 NTU for 80:20% composition while the highest value of 16.45 NTU generated from 100:0%. The result occurred due to the properties of its porous structure and high surface area, is effective in removing small particulates and certain organic compounds through physical adsorption (Susilawati et al. 2022; Syafalni et al. 2013). On the other hand, activated

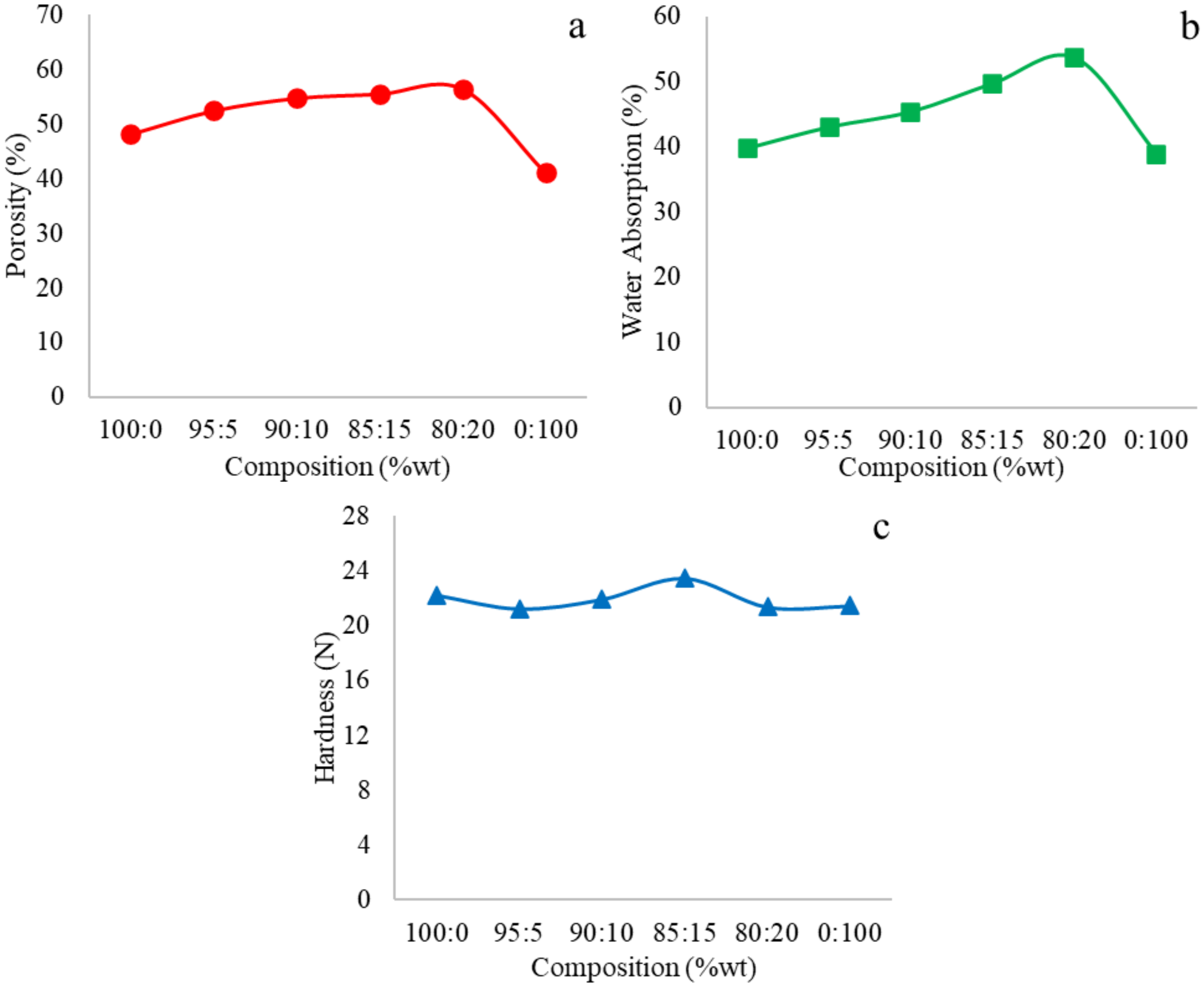


FIGURE 6. Porosity graph of various adsorbent composition (a), Water absorption of various adsorbent composition with variation composition (b), and Hardness graph of various adsorbent composition (c)

TABLE 3. Characteristic of raw peat water

Parameter	Unit	Value	Standard
Turbidity	NTU	31.32	≤25
Color	TCU	175.4	≤50
Iron (Fe)	mg/L	1.443658	≤0.3
Manganese (Mn)	mg/L	0.765154	≤0.4
pH	-	5	6.5-8.5

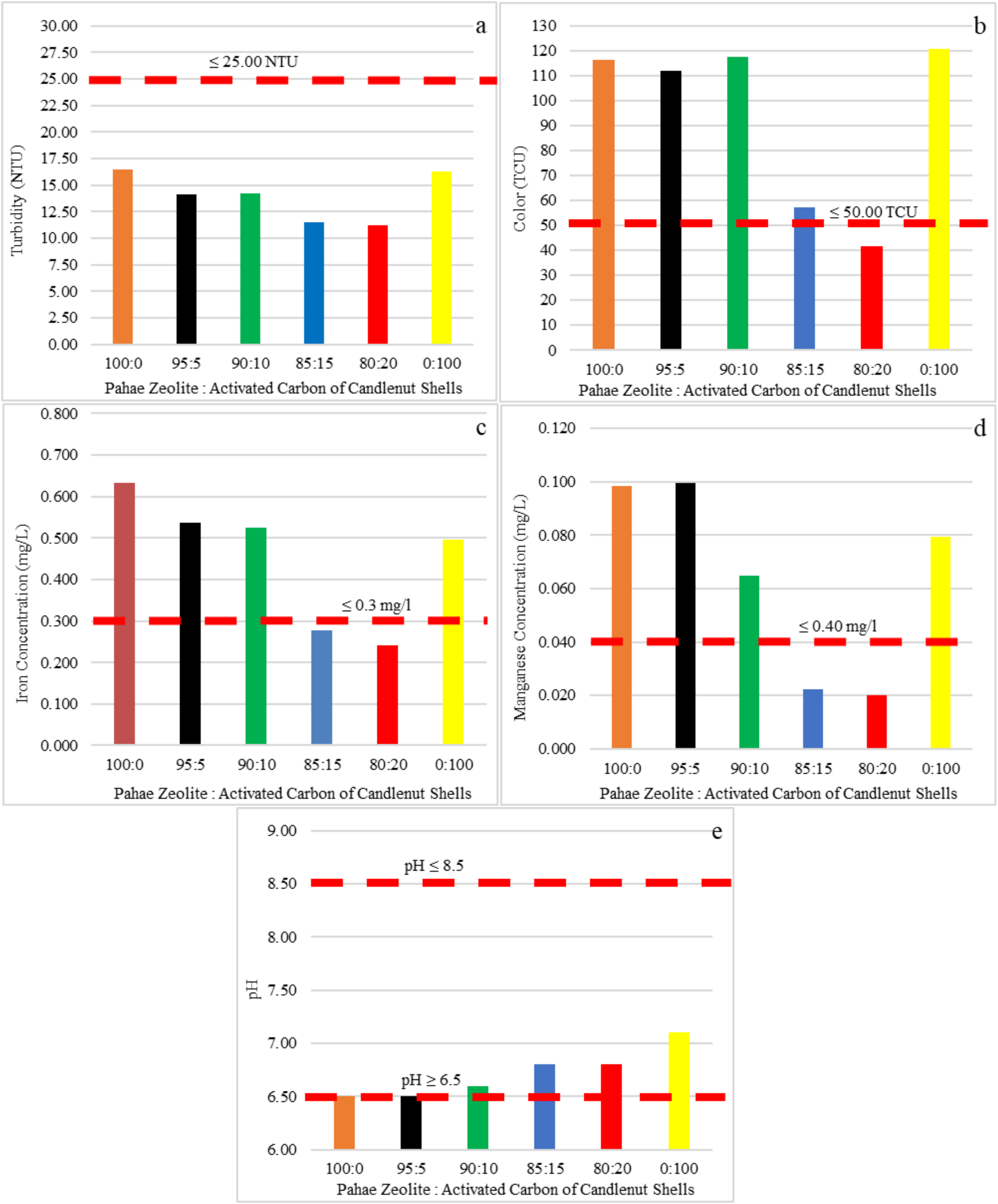


FIGURE 7. Peat water purification results from various adsorbent compositions: (a) turbidity, (b) color, (c) iron concentration, (d) manganese concentration, and (e) pH

carbon from candlenut shells, with its extensive pore structure and high adsorption capacity, is particularly adept at removing color and dissolved organic contaminants through adsorption. The optimal reduction in turbidity at an 80:20 ratio of zeolite to activated carbon suggests a synergistic effect where the mechanical filtration properties of zeolite combined with the organic adsorption capacity of activated carbon result in superior turbidity reduction. The diminished performance at a 100:0 ratio, where only zeolite was used, indicates the necessity of activated carbon to achieve the lowest turbidity, highlighting the importance of targeting both particulate and dissolved organic matter in peat water treatment.

The effectiveness of different ratios of natural Pahae zeolite and activated carbon derived from candlenut shells in reducing water color, measured in True Color Units (TCU) is presented in Figure 7(b). The data show a clear trend where increased proportions of activated carbon enhance color reduction, with the 80:20 ratios significantly lowering color levels from initial raw peat water of 175.4 TCU to 41.7 TCU, below the acceptable threshold of ≤ 50.00 TCU. This improvement in color reduction is largely attributed to the activated carbon's inherent characteristics. Activated carbon is renowned for its high adsorption capacity due to its extensive internal pore structure, which provides a large surface area for adsorption (Saad et al. 2020a, 2020b). This structural advantage enables it to efficiently adsorb a wide range of organic molecules and chromophoric (color-causing) compounds that are often present in peat water, such as humic acids and fulvic acids. These compounds are responsible for the water's brownish tint and are challenging to remove solely by physical methods. The capacity of activated carbon to interact with organic compounds, particularly through non-polar adsorption, makes it an indispensable component in the treatment of colored water.

Figure 7(c) and 7(d) demonstrates that increasing proportions of activated carbon in mixtures with natural Pahae zeolite significantly enhance the reduction of iron and manganese concentrations in peat water, bringing them below the acceptable limits of ≤ 0.3 mg/L for iron and ≤ 0.4 mg/L for manganese. The initial concentrations of 1.44 mg/L for iron and 0.76 mg/L for manganese were notably reduced in the 80:20% zeolite to activated carbon mixture, achieving the lowest concentrations of 0.242 mg/L and 0.020 mg/L, respectively. In contrast, mixtures containing 100% zeolite yielded higher residual concentrations, with iron at 0.632 mg/L and manganese at 0.098 mg/L. While Pahae zeolite primarily aids adsorbing some metal ions through ion-exchange mechanisms, its capacity for heavy metal removal is considerably enhanced with the addition of activated carbon. This enhanced purification effect is primarily due to the adsorptive properties of activated carbon, which, with its large surface area and chemically active functional groups like hydroxyls and carboxyls, effectively binds and chelates metal ions (Saad et al. 2020a, 2020b; Susilawati et al. 2023, 2022). The synergistic interaction between zeolite and activated carbon in the 80:20% ratio maximizes metal removal, illustrating the crucial role of activated carbon in achieving optimal performance in peat water treatment systems, particularly for areas heavily contaminated with metals.

Figure 7(e) illustrates the pH levels in water treated with varying compositions of natural Pahae zeolite and activated carbon from candlenut shells, indicating how different ratios affect pH stability. The sample with 100% Pahae zeolite shows a pH close to 6.5, just meeting the minimum acceptable limit. This slight decrease in pH can be attributed to the ion exchange properties of zeolite, where metal cations like sodium, calcium, or magnesium may replace hydrogen ions in water, slightly reducing the pH. As the proportion of activated carbon increases in the mixtures (from 95:5 to 80:20), there is a noticeable shift toward a neutral pH around 7. This is due to activated carbon's ability to buffer the water, absorbing acidic or basic compounds, and stabilizing the pH through its extensive porous structure that interacts with hydrogen and hydroxide ions (Fatimah et al. 2023; Mistar et al. 2018). In the composition with 100% activated carbon, the pH approaches 8.5, remaining within the safe upper limit of ≤ 8.5. This rise suggests that activated carbon, especially from organic sources such as candlenut shells, may introduce basic components or more effectively remove acidic compounds, thereby elevating the pH. The pH adjustment mechanism in these treatments primarily involves the adsorption characteristics and ion exchange capabilities of the materials (Mariana et al. 2022, 2021). Pahae zeolite's rich aluminosilicate content typically engages in cation exchange with water's hydrogen ions, potentially lowering the pH, whereas activated carbon's buffering action involves either adsorbing excess hydrogen ions or occasionally releasing basic ions to raise and stabilize the pH. This ability to control pH is crucial in water treatment processes, ensuring the effectiveness of subsequent treatment stages, including disinfection and contaminant removal, while complying with environmental standards and safeguarding water quality.

The study further elucidates the importance of solution pH in adsorption processes, as pH variations can considerably influence metal binding and organic adsorption efficiencies (Rangel-Mendez & Streat 2002). Under acidic conditions, certain metal ions, such as Fe(III) and Mn(II), are more readily adsorbed due to increased electrostatic attraction and protonation effects on the adsorbent surface. In contrast, basic conditions may enhance the adsorption of some organic compounds, as deprotonation at higher pH values typically increases the negative charge density on adsorbents, thereby attracting positively charged metal species (Kithinji Kinoti et al. 2022). These findings highlight how the acidic nature of peat water can be leveraged to improve the adsorption of metals while necessitating careful pH adjustment to maximize the adsorption of various organics effectively.

Figure 8 systematically illustrates the purification process using adsorbents made from Pahae natural zeolite and activated carbon, clarifying the fundamental mechanisms involved in the adsorption of salts and minerals from peat water. The zeolite's pore sizes vary from 49.26 to 84.67 Å, which are suitable for accommodating water molecules and ions with single and double charges. However, the entry into these pores is restricted to molecules and ions of appropriate size, giving the zeolite a 'molecular sieving' property. Furthermore, the adsorptive qualities of activated carbon bolster this process. The combination of these materials enables the effective removal of diverse dissolved salts and minerals by leveraging the unique properties of each adsorbent. Pahae natural zeolite primarily acts as a molecular sieve, selectively filtering out ions that do not fit into its pores. Its structural network, marked by consistently sized pores and channels, facilitates the selective adsorption of these cations. During purification, these cations in peat water are preferentially exchanged with the zeolite's native cations. This ion exchange is promoted by the zeolite's negatively charged alumino-silicate framework, which attracts the positively charged peat water ions. The process is highly selective, ensuring retention of only those ions that match the pore size requirements. This selectivity is largely determined by the ionic radius and charge density of the ions, enhancing the zeolite's capability to purified peat water.

Additionally, activated carbon is essential for eliminating organic substances and larger inorganic molecules, thanks to its vast internal surface area created by a complex arrangement of micro, meso, and macropores. This structure offers ample sites for adsorbing these larger molecules through van der Waals forces and various non-covalent interactions. This physical adsorption process enhances the ion exchange capabilities of zeolite by trapping non-ionic and larger molecular contaminants that bypass the zeolite's molecular sieving function. The combined use of these adsorbents in the purification process provides a thorough method for purifying peat water. As water flows through layers of zeolite and activated carbon, a step-by-step filtration mechanism occurs. The zeolite initially selectively removes specific ions based on their size and charge, followed by the activated carbon layers capturing organic and larger inorganic molecules. This ensures the water is not only reduced in organic content but also largely cleared of a broad spectrum of contaminants. This coordinated adsorption strategy represents a significant progression in sustainable purification technology, delivering an efficient method for producing drinkable water from peat water and addressing the environmental and economic issues linked with traditional purification methods.

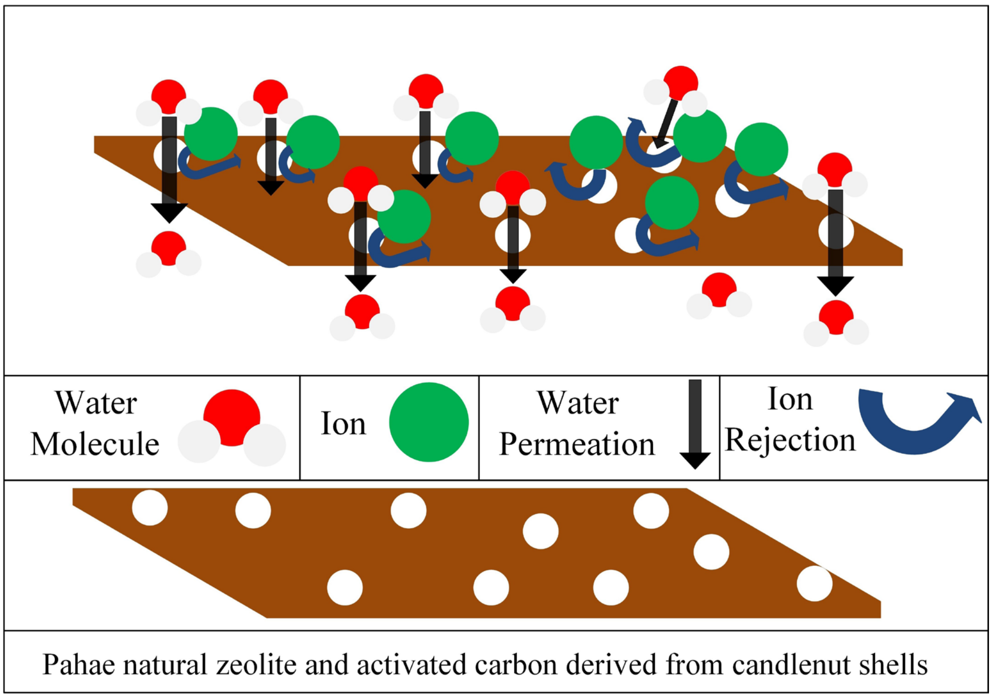


FIGURE 8. Peat water purification mechanism using Pahae natural zeolite and activated carbon derived from candlenut shells with variation composition

CONCLUSION

The comprehensive evaluation of Pahae natural zeolite and activated carbon derived from candlenut shells, using various analytical techniques, establishes a robust foundation for optimizing adsorbent materials in peat water treatment applications. X-ray fluorescence (XRF) and energy-dispersive X-ray (EDX) analyses confirmed a notable enhancement in silica content and elemental purity after chemical activation with potassium hydroxide (KOH). Meanwhile, scanning electron microscopy (SEM) and X-ray diffraction (XRD) provided insights into critical morphological and structural changes, such as increased surface roughness, pore size, and pore distribution, which are pivotal in enhancing adsorption capacity. These changes, specifically the development of mesopores and macropores, effectively improve the material's ability to capture larger organic molecules and heavy metals, as they create accessible pathways and additional surface area for contaminant binding. These changes are critical in enhancing the material's performance in water purification processes, as evidenced by the physical property assessments which showed that varying the zeolite-to-carbon ratio can significantly influence porosity, water absorption, and hardness, directly correlating with the efficiency of purification. The purification analysis underscored the effectiveness of the adsorbent materials in significantly reducing turbidity, color, and metal concentrations in peat water, aligning with environmental standards. The study concludes that the strategic combination of Pahae natural zeolite with activated carbon not only optimizes the physicochemical properties of the adsorbents but also significantly enhances their efficiency in purifying peat water, making it a viable solution for sustainable water management practices. This synergy between the materials provides a tailored approach to addressing specific water quality issues, showcasing their potential in advanced water treatment technologies.

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