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ENHANCED REMOVAL OF NAPHTHOL YELLOW DYES FROM WATER BY BIOCHAR FROM KAPOK RANDU STEMS (*Ceiba pentandra*)

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ABSTRACT

The study focuses on how biochar made from Ceiba pentandra (kapok randu) stems can effectively remove Naphthol Yellow dyes from water. The biochar was produced by heating kapok stems at 400°C, 450°C, 500°C, and 550°C, and its moisture and ash content were determined in accordance with the Standard SNI 06-3730-1995. The physical and chemical properties of the biochar were analyzed using SEM-EDS, which confirmed the presence of mesopores on its surface. Adsorption experiments were conducted to evaluate the biochar's effectiveness in removing Naphthol Yellow dyes, adjusting factors such as contact time, dye concentration, and biochar dosage. The adsorption process used second-order kinetics and the Langmuir isotherm model, which means that the dye stuck to a smooth surface in a single layer. The results showed that biochar made from kapok stems is highly efficient and cost-effective, removing 36.13% of Naphthol Yellow dye in just 50 minutes using 75 mg of adsorbent. This study highlights the potential of using agricultural waste-derived biochar for water treatment and supports the development of sustainable methods for dye removal from wastewater.

Keywords: Pyrolysis, Kapok Randu, Biochar, Adsorption, Dyes.

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INTRODUCTION

Water is a very important natural resource for human life and for the ecosystem as a whole. On the other hand, water pollution by various chemical substances, including synthetic dyes produced from, for example, the batik industry, may pose a serious threat to the quality of water and environmental health. Dyes are often used in the textile industry,[1] printing,[2] and other manufacturing processes such as the paint and coating industry,[3] and the effluents from these industries often pollute the water environment with dyes that are difficult to break down naturally. Dye pollutants in water not only disturb the aesthetic function of water but can also harm the living organisms within it.[4] Dispersed dyes in water can disrupt the photosynthesis processes for aquatic plants and damage aquatic ecosystems.[5] Additionally, some dyes are considered harmful to human health, especially if they bioaccumulate through the food chain.[6] Due to the difficulties identified earlier, various methods have been developed in an attempt to solve the problem of dye pollution in water.[7] It is a product of the carbonization of organic materials such as biomass and is attracting increasing attention due to its performance as an effective agent of adsorption in the removal processes of various contaminants in water and soil. Kapok randu (*Ceiba pentandra*) stems are one of the abundant and widely available biomass sources in various tropical regions. The use of kapok randu stems as raw material for biochar production can be an attractive alternative because it can reduce organic waste that is usually just thrown away. Although the potential of kapok seeds as a Lead (Pb) adsorbent has been demonstrated,[8] the use of biochar from kapok randu stems for decolorization of dyes in water still requires further research to understand its effectiveness and influencing factors. Therefore, this research seeks to examine the ability of biochar prepared from the kapok randu stem to remove naphthol yellow in contaminated water. The problem-solving approach in this study involves a series of experimental and analytical steps, namely sample collection, biochar preparation by pyrolysis process, biochar characterization by Scanning Electron

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Microscopy (SEM), decolorization test, and analysis of decolorization results by Langmuir adsorption isotherm model. The findings provide valuable insights into the potential use of biochar from kapok randu stems, as well as contributing to the development of effective methods for addressing water pollution problems. The preparation of biochar for dye decolorization in water has shown that biochar has promising potential as an adsorption agent for the removal of organic contaminants such as dyes from water.[9] The generation of biochar is characterized by the use of various feedstocks, such as agricultural waste,[10] hardwood,[11] and other biomass.[12] Consequently, biochar is effective in reducing the color and concentration of dyes in water through adsorption mechanisms.[13] The use of kapok randu (Ceiba pentandra) stems as raw materials for biochar production has not yet received enough attention among the various biochar raw materials studied as dye adsorbents. Therefore, the novelty of this research lies in the use of kapok randu stem as a raw material for biochar manufacture, which has the advantage of being an abundant source of biomass,[14] has the potential to be a sustainable alternative to overcome the problem of dye pollution in water.

EXPERIMENTAL

Materials and Methods

Naphthol yellow (dye), Buffer solution, Distilled water as solvent, Kapok randu stems as raw material, porcelain cup, furnace for pyrolysis, Sieve for adhering to the PAC Powder Active Carbon standard, Volumetric flask for adsorption process, and Filter paper.

General Procedure

The raw materials were dried in the sun after washing and cutting them into pieces, followed by a pyrolysis process by heating the dried kapok and randu stems in the absence of oxygen at temperatures: 400 °C, 450 °C, 500°C, and 550 °C. The pyrolysis process produces a solid black material as its product. The yield is calculated. Next, we sieve the biochar using an 80-mesh size, adhering to the PAC Powder Active Carbon standard. The smaller the particle diameter, the greater the surface area, resulting in greater adsorption ability. We then analysed and characterized the biochar for moisture content, ash content, pore morphology (by SEM), and determination of carbon and other elements (by EDS). Decolorization of dyes in contaminated water was measured using UV-Vis Spectroscopy. Determination of the optimum concentration was carried out by making variations in the concentration and contact time. The adsorption results of each variation were calculated using the formula of adsorption capacity (*Qe*) and adsorption power (% adsorption).[15]

$$Qe = \frac{(\mathrm{Co} - \mathrm{Ce}).\mathrm{v}}{\mathrm{m}}$$

$$\%\ \text{Adsorption} = \frac{\mathrm{Co}-\mathrm{Ce}}{\mathrm{Co}}\ \mathrm{x}\ 100\%$$

Explanation: *Qe* represents the adsorption capacity of the biochar at equilibrium, Co denotes the initial concentration (mg/L), Ce indicates the equilibrium concentration (mg/L), V signifies the volume of the solution (L), and m refers to the mass of the biochar adsorbent (g).

RESULTS AND DISCUSSION

Biochar Preparation

Biochar yield, or the percentage of biochar produced from the initial biomass after pyrolysis, is highly dependent on the type of biomass used and the pyrolysis conditions, including temperature. Table-1 below shows the yield results of biochar derived from kapok randu stems with pyrolysis temperatures of 400 °C, 450 °C, 500 °C, and 550 °C, where the biochar yield tends to decrease as the pyrolysis temperature increases because more organic volatiles are released at higher temperatures, leaving behind less solid carbon residue.[16]

Moisture and Ash Content

Both water and ash content were measured; each provides insight into the quality of biochar. Measurement of moisture content allows for the production of biochar with consistent quality. High moisture content in biochar may indicate incomplete pyrolysis or contamination during storage, which can reduce the total

carbon content measured within the biochar. Thus, knowing the moisture content is crucial for accurate calculation of biochar composition.

Table-1: Biochar Yield with Various Pyrolysis Temperatures

Kapok randu stem (g)	Pyrolysis temperature (°C)	Yield (g)	Percentage (%)
200	400	64.2	32.1
200	450	54.4	27.2
200	500	46.6	23.3
200	550	45.0	22.5

On the other hand, high ash content suggests the presence of more inorganic impurities or non-carbon material, which can lower biochar's effectiveness as an adsorbent. Ash can affect the pH, cation exchange capacity (CEC), and adsorption properties of biochar. Therefore, measuring ash content is essential to determine how biochar will interact with the environment or application medium. The summary of the moisture and ash content measurements for biochar from Kapok randu stems is presented in Table-2 below.

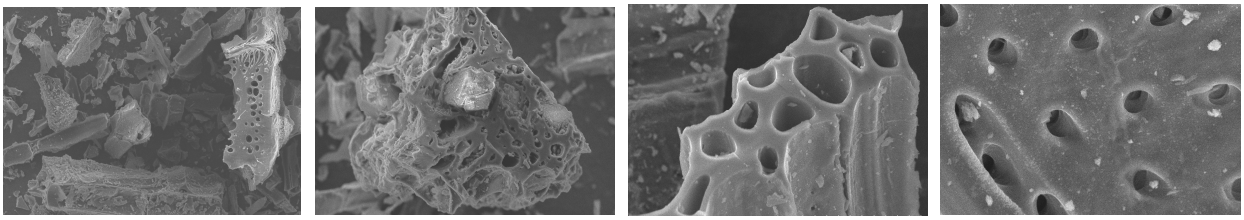
Table-2: Moisture and Ash Content of Biochar from Stems of Kapok Randu

Pyrolysis temperature (°C)	Moisture Content (%)	SNI 06-3730- 1995	Ash content (%)	SNI 06-3730- 1995
400	5.2	10%	6.9	15%
450	5.0	10%	7.1	15%
500	4.8	10%	7.8	15%
550	4.7	10%	8.0	15%

Table-2 presents the moisture and ash content of biochar produced from the kapok randu stems (KRS) at different pyrolysis temperatures. The ash and moisture contents are all within acceptable limits set by the Standard SNI 06-3730-1995. Moisture content displays a decreasing trend with an increase in pyrolysis temperature; that is, drying occurs at higher temperatures.[16] On the other hand, ash content increases slightly between 500°C and 550°C because more organic material decomposes, leaving more mineral residues.[17]

Pore Characterization

In this study, the physical properties of the biochar were characterized using SEM. SEM allows for detailed observation of the pore structure and surface of biochar. These pores play an important role in determining the adsorption capacity of biochar for substances such as water, nutrients, and pollutants. Understanding the pore and surface structure helps predict how biochar interacts with environmental pollutants, such as heavy metals and organic compounds. Figure-1 presents the characterization of the pores in biochar produced from thermally treated kapok tree branches at 450°C.

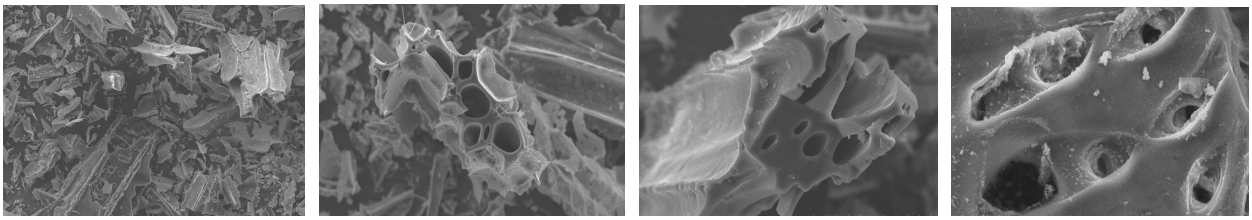


(a) (b) (c) (d)

Fig.-1: SEM Analysis of Biochar from Kapok Randu Stems, which is Produced with the Temperature Pyrolysis 450°C with Enlargement 500x (a), 1000x (b), 2500x (c), and 5000x (d)

Porous materials are classified by IUPAC into three groups based on pore size: micropores (less than 2 nm in diameter), mesopores (2 to 50 nm in diameter), and macropores (more than 50 nm in diameter). Every pore serves a distinct purpose in the process of absorption. The pores present on the surface of biochar from kapok randu pyrolyzed at 450°C are predominantly mesopores, although there are some micropores as well. The principal function of mesopores is to sequester ingested substances and act as a gateway to the micropore.[18] Mesopores have the ability to incorporate molecules that are somewhat larger than those that can be accommodated within micropores.[19] They are also capable of accommodating certain macromolecules. Mesopores function as a supplementary storage for adsorbates and also enable the

movement of adsorbates to smaller-sized micropores.[20] Consequently, this facilitates a more effective overall adsorption process. Mesopores offer supplementary capacity that aids in decreasing pore density, thereby improving the conductivity of gas or liquid within the adsorbent material. Similarly, to the biochar produced at a pyrolysis temperature of 450 °C, increasing the temperature to 500 °C does not significantly change the pore size of the biochar, which is predominantly composed of mesopores (< 50 nanometers), although it still contains some micropores (< 2 nanometers), as shown in Fig.-2.



(a) (b) (c) (d)

Fig.-2: SEM Analysis of Biochar from Kapok Randu Stems, which is Produced with the Temperature Pyrolysis 500 °C with Enlargement 500x (a), 1000x (b), 2500x (c), and 5000x (d)

With an increase in temperature, biochar structure becomes more stable due to the development of a graphitic matrix. This structure is not only more resistant to chemical degradation but also maintains the pore size and distribution formed during the pyrolysis process. Biochar with more micropores has a higher adsorption capacity for small molecules like water and gas. In contrast, biochar with more mesopores and macropores, typically formed at higher pyrolysis temperatures, is more effective at adsorbing larger molecules such as nutrients or organic pollutants. The effect of pyrolysis temperature on pore size also depends on the type of raw material used. For instance, lignin-rich raw materials tend to produce biochar with higher porosity at higher temperatures compared to materials rich in cellulose or hemicellulose. Kapok randu fruit contains 14-58% lignin, and 65-67% cellulose,[21] so its porosity will vary according to the pyrolysis temperature. The combination of mesopores and micropores enhances the diffusion of molecules into the structure of biochar or carbon. Mesopores act as a "highway" that allows larger molecules and water to move quickly toward micropores, where they can then be adsorbed. This accelerates the overall adsorption process and improves efficiency.

Element Analysis

Figure-3 shows that Carbon is the main element at 71.32% and is normally crucial to ensure adsorption capability. The porosity structure of carbon can actually provide very many sites for adsorption, hence improving the capacity of biochar to absorb various pollutants or substances. The other element present in biochar is Oxygen at 19.52%, normally resulting from the oxygen functional groups present on the surface of the biochar. These are the groups that can contribute to the adsorption capacity by means of polar interactions or hydrogen bonding with the adsorbed substances. Other elements like Mg, P, S, K, Ca, and Fe may contribute to or influence the adsorption capacity by binding or by ion exchange.[22]

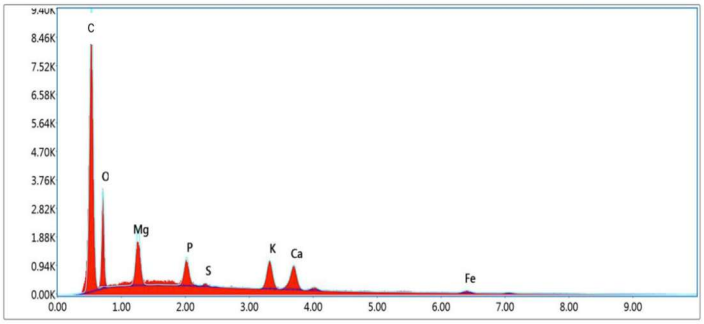


Fig.-3: Element Analysis by Energy Dispersive Spectroscopy (EDS)

Adsorption Capacity Analysis Based on Variations in Biochar Weight

The measurement of biochar's ability to adsorb Naphthol yellow was conducted with three variations: variations in biochar weight, variations in reaction time. Table-3 explained that increasing the weight of

biochar generally increases the amount of naphthol yellow removed, which is reflected in the increase in *Qe* and adsorption values (%) with higher biochar weights.

Tabel-3: Quantitative Analysis of Adsorbent Weight on Adsorption Capacity

Biochar weight (mg)	Contact time (min)	Abs	Co (mg/L)	Ce (mg/L)	Volume	*Qe* (mg/g)	EAZW(%)
25	60	0.383	15	14.9911	0.01	0.0017	0.05
50	60	0.367	15	14.2800	0.01	0.2880	4.80
75	60	0.290	15	9.5803	0.01	0.7226	36.13
100	60	0.305	15	10.1686	0.01	0.4831	32.20

The equilibrium concentration decreases as the biochar weight increases, indicating that more naphthol yellow is being removed with greater amounts of biochar. As seen in Fig.-4, the Qe value increases with higher biochar weights, showing that more naphthol yellow is being adsorbed per gram of biochar. The percentage of contaminant removed increases with biochar weight, reaching its highest value at 75 mg of biochar, suggesting that this amount is most efficient in removing the Naphthol yellow from the solution. Increasing the amount of biochar generally enhances its ability to adsorb the contaminant, with the optimal performance observed at 75 mg of biochar in this specific setup. Lower absorbance values generally correspond to higher contaminant removal, suggesting more effective treatment.[23]

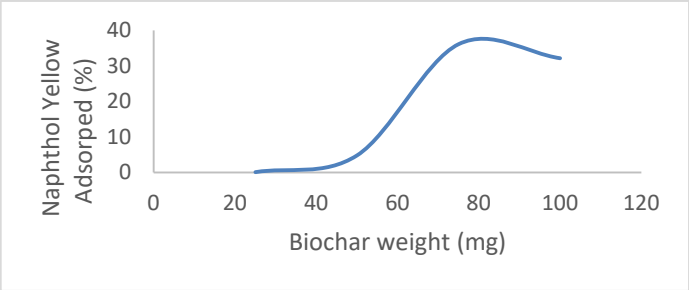


Fig.-4: Isotherm Adsorption Curve of Biochar Weight vs Naphthol Yellow Adsorption (%)

Adsorption Capacity Analysis Based on Reaction Time

Table-4 illustrates the strong dependence of adsorption efficiency and capacity on contact time. The most efficient adsorption occurs within the first 50 minutes, after which the system reaches a quasi-equilibrium state, where further increases in contact time provide diminishing returns. This behaviour is typical in adsorption processes, where the adsorbent's surface sites become increasingly saturated, slowing the rate of adsorption over time.

Table-4: Quantitative Analysis of Reaction Time of on Adsorption Capacity

Biochar weight (mg)	Contact time (min)	Abs	Co (mg/L)	Ce (mg/L)	Volume (L)	*Qe* (mg/g)	EAZW (%)
75	20	0.306	15	11.5688	0.01	0.4573	22.87
75	30	0.287	15	10.7244	0.01	0.5693	28.50
75	40	0.256	15	9.3466	0.01	0.7533	37.68
75	50	0.241	15	8.6800	0.01	08426	42.13
75	60	0.242	15	8.7244	0.01	0.836	41.83

The increasing values of Qe and EAZW show that adsorption is a process that depends on time, where biochar captures more of the adsorbate. In the first 20 to 50 minutes, the rate of adsorption is high, which is evident from the rapid rise in Qe and EAZW. This happens because there are plenty of active sites on the biochar for the adsorbate to bind to. Around 50 minutes, the system starts to approach equilibrium, where adsorption and desorption (adsorbate leaving the biochar) happen at similar rates. At this point, the biochar's capacity to take up more adsorbate slows down, shown by the leveling off of Qe and the slight decrease in EAZW after 50 minutes. After 50 minutes, the biochar likely reaches its saturation point, where most of its active sites are occupied by the adsorbate. This is why extending the contact time beyond 50 minutes provides fewer benefits, as seen by the leveling off of Qe and the slight drop in EAZW. The data suggests that 50 minutes is the ideal contact time for maximum adsorption efficiency. Extending it further

gives only small improvements and may even lower efficiency, as shown by the decrease in EAZW from 42.13% to 41.83% at 60 minutes.

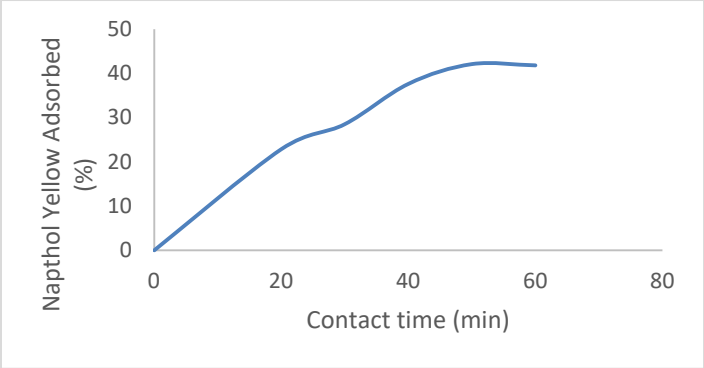


Fig.-5: Isotherm Adsorption Curve of Contact Time (min) vs Naphthol Yellow Adsorption (%)

The strong relationship between contact time and adsorption efficiency is shown in Fig.-5. The best adsorption happens in the first 50 minutes, after which the system reaches a near-equilibrium state, with diminishing returns from longer contact times. This is common in adsorption processes, as the adsorbent's surface sites become saturated over time, slowing down adsorption.[24]

CONCLUSION

The current study illustrates the effectiveness of biochar derived from Ceiba pentandra, specifically its stem, in eliminating naphthol yellow dye from contaminated water. Pyrolysis within a 400–550 °C temperature range produced biochar with highly favorable physical and chemical characteristics, and its mesoporous nature significantly enhanced its adsorption potential. Adsorption followed second-order kinetics and fitted the Langmuir isotherm model. Optimal conditions for dye removal were 36.13% within 50 minutes with 75 mg of biochar. The results indicate that biochar derived from kapok randu stems is an economical and sustainable approach to mitigating water pollution, especially for industries that release synthetic dyes into aquatic environments. This research underscores the potential of utilizing agricultural waste as a useful resource for environmental remediation, facilitating the advancement of sustainable and effective techniques for treating dye-contaminated wastewater. We recommend further studies to investigate the scalability of this process and the effectiveness of biochar in treating other pollutants.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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