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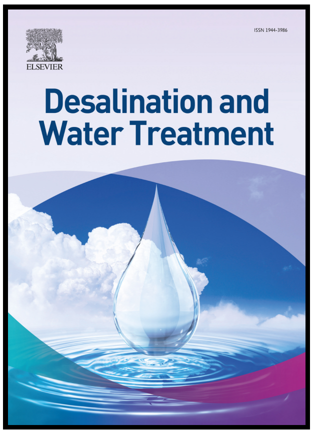

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Integration of IoT and Heterogeneous Fenton Process Using Biochar–Zeolite Catalysts for Batik Wastewater Treatment

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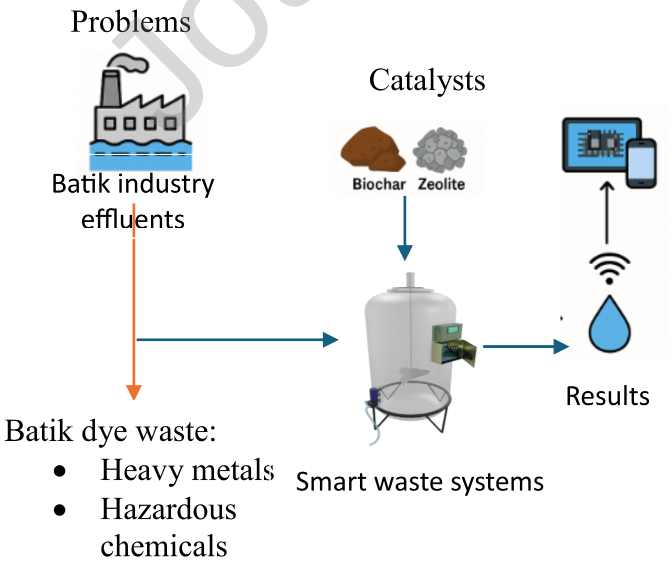
Abstract

The batik industry generates wastewater containing dyes, heavy metals, and hazardous chemicals that cause serious environmental pollution. This study introduces an Internet of Things (IoT)-enabled wastewater treatment system integrating real-time monitoring with a heterogeneous Fenton process using biochar and natural zeolite catalysts. Biochar, derived from sugarcane bagasse by pyrolysis, and natural zeolite with high ion-exchange capacity were modified through Fe impregnation to enhance catalytic activity. Characterization using BET, SEM–EDX, and UV–Vis spectrophotometry confirmed porous morphology, surface area, and elemental composition supporting performance. The IoT platform with sensors and microcontrollers monitored parameters such as pH and temperature, ensuring process optimization. The system achieved up to 95% dye removal, with red and orange dyes showing the highest efficiency. Recyclability tests showed zeolite maintained stable performance over four cycles, while biochar declined due to pore saturation and temporary catalytic activity. The novelty of this work lies in combining IoT-based monitoring with eco-friendly catalysts to create a cost-effective and scalable solution. Designed for small and medium enterprises, the system reduces environmental impact, supports regulatory compliance, and provides a practical pathway toward sustainable wastewater management aligned with global sustainability goals.

Graphical abstract



Keywords: Batik; Biochar; Heterogeneous Fenton; Internet of Things (IoT); Smart Waste; Zeolite

Introduction

Batik is one of Indonesia's cultural heritages that has gained global recognition and was designated as an Intangible Cultural Heritage of Humanity by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) on October 2, 2009 [1]. The batik production process involves several stages, including painting designs, coloring, washing, and waxing. However, this process generates liquid waste containing complex organic compounds, such as azo dyes, heavy metals, and other hazardous chemicals [2]. If not properly managed, this waste can negatively impact the environment by polluting water sources, damaging ecosystems, and endangering the health of surrounding communities [3]. With the increasing production of batik across various regions in Indonesia, managing batik waste has become an increasingly urgent issue to address.

Liquid waste from the batik production process is complex and contains high concentrations of hazardous chemicals, making it challenging to treat using conventional methods [4]. For example, azo dyes commonly used in batik coloring are resistant to natural biodegradation processes [5]. Furthermore, the presence of heavy metals such as chromium and copper in this waste significantly increases its toxicity [6]. An innovative and effective approach is needed for batik waste management that is not only able to reduce the content of pollutants significantly, but also meets the principles of sustainability and environmental friendliness. [7].

One promising approach to batik waste management is the use of the Fenton heterogeneity method [8], [9]. The heterogeneous Fenton process uses an iron-based catalyst to generate highly reactive hydroxyl radicals (-OH) [10]. These radicals can break down complex organic compounds into simpler and less dangerous compounds [11]. Compared with the conventional Fenton method, the heterogeneous approach has advantages such as catalyst reuse, reduced chemical residues, and higher efficiency under varying operating conditions [12]. In this study, biochar and zeolite were used as supporting media for heterogeneous Fenton catalysts. Biochar, derived from biomass waste such as sugarcane bagasse, exhibits excellent physicochemical properties, including a large surface area, well-developed pore structure, and high adsorption capacity. Meanwhile, zeolite provides exceptional ion exchange capacity and thermal stability, making it an ideal complement to biochar in supporting catalytic reactions [13].

However, batik waste processing does not only require chemical solutions, but also innovative technological approaches. Internet of Things (IoT) based technology offers a modern solution to manage waste processing efficiently [14]. By integrating IoT devices into wastewater treatment systems, monitoring of parameters such as temperature, pH, and contamination levels can be done in real-time [15], [16]. This technology not only improves operational efficiency, but also enables remote control and process automation [17]. In this research, an IoT-based smart waste system was designed to optimize batik waste processing using biochar and zeolite as catalysts. The system comprises components such as sensors, microcontrollers, pumps, and monitoring applications, enabling users to monitor and control the system remotely.

In addition, the development of an IoT-based smart waste system provides added value in terms of efficiency and transparency of the waste processing process [18]. System users can monitor performance through a web-based application or custom-designed software. The monitoring includes key parameters such as the pollutant degradation rate, operating time, catalyst condition, and reaction temperature. With these features, the system enables users to make more informed and responsive decisions in response to changing environmental conditions. The implementation of IoT-based smart waste technology is expected to provide a viable solution for adoption by small and medium enterprises (SMEs) in the batik industry. Many SMEs face limitations in budget, technology, and technical expertise, making it challenging to manage waste effectively. This system is designed with these constraints in mind, ensuring affordability and ease of implementation. Furthermore, this approach aligns with government policies aimed at reducing environmental pollution while enhancing the competitiveness of the batik industry in the global market.

Therefore, this study aims to develop a smart waste management approach by combining IoT technology and the heterogeneous Fenton method using biochar and zeolite. The designed system not only focuses on waste treatment, but also attempts to integrate energy efficiency and sustainability in the process. In this case, the biochar used comes from local biomass waste, such as sugarcane bagasse, which is a renewable and abundant resource. In this way, the proposed approach not only offers a solution to the problem of batik waste, but also supports the principle of a circular economy by utilizing waste as a new resource.

Experimental Method and Material

a) Feed Water Characteristics

The feed water used in this study was raw batik wastewater collected from a local batik production site. Prior to treatment, the wastewater was filtered to remove large, suspended solids but was not chemically pre-treated. The concentrated wastewater had an initial dye concentration of 140.476 mg/L, which represents the actual strength of the industrial effluent. For the purposes of this study, the wastewater was diluted to 20 mg/L to provide a more controlled condition for adsorption and catalytic experiments. The baseline characteristics of the wastewater included a pH of 9.2, and temperature of 28–30 °C. These conditions served as the reference point for evaluating the adsorption and degradation performance of the heterogeneous Fenton process.

b) Preparation of biochar dan zeolite

Biochar was produced from sugarcane bagasse through a pyrolysis process conducted at 500°C with a heating rate of 10–12°C/min. This process yielded high-quality biochar with a high carbon content, a large surface area, and an ideal pore structure for adsorption applications. Following pyrolysis, the biochar was sieved to a particle size of <100 µm to maximize the contact surface area. This method adheres to the procedure outlined in previous studies [9] without any significant modification. Meanwhile, zeolite raw materials were chosen as catalyst support media because of their superior properties in ion exchange and adsorption capabilities [19]. In this study, the zeolite used was natural zeolite sourced from local deposits in Indonesia. It was selected due to its affordability, wide availability, and high ion-exchange capacity, making it suitable as a support material for heterogeneous Fenton catalysts. Prior to use, the zeolite was cleaned and heated at 60 °C for one hour to remove residual moisture and impurities. The materials were then combined in a total ratio of 50 grams and mixed until a homogeneous mixture was achieved, making it ready for use as a catalyst developer. This procedure integrates the adsorption properties of biochar with the ion exchange capabilities of zeolite, thereby enhancing efficiency in catalytic applications [20].

c) Preparation Catalyst using impregnation method

The catalyst preparation was synthesized using the wet impregnation method, where the precursor solution $Fe(NO_3)_3 \cdot 9H_2O$ in isopropanol with a concentration of 0.09 M served as a source of Fe^{3+} ions. A total of 5 grams of biochar and 5 grams of zeolite were used as supporting media, because of their properties which have a high surface area and good pore structure, so they can increase the active dispersion of metals. This mixture was processed using an ultrasonicator for one hour to achieve even impregnation and ensure that Fe^{3+} ions are optimally adsorbed onto the surface of the supporting media [21], [22]. After the impregnation process, the mixture was dried at room temperature for 24 hours to evaporate the solvent without causing material agglomeration. The final stage involved calcination at 300°C for three hours in a furnace with an inert atmosphere or limited air. This step was designed to remove nitrate residues, strengthen metal-matrix bonds, and create stable metal oxide active sites. The resulting product is a heterogeneous catalyst ready for use in batik wastewater degradation, particularly in heterogeneous Fenton reactions [21].

d) Development of IoT-based smart waste technology

This research integrates an Internet of Things (IoT) system into smart waste technology designed to support batik waste management and prevent pollution in real time. The system incorporates various electronic components, including sensors, data processing modules, gearbox motors, and water pumps. Sensors monitor key parameters such as temperature, pH, and removal levels in the waste. The collected data are transmitted to an ESP32 or ATmega128 module, which serves as the primary processor, offering fast processing capabilities and supporting IoT communication. The motor gearbox and water pump regulate the circulation and distribution of waste, with electric current control managed through electronic relays to ensure energy efficiency and operational stability. This IoT system connects the hardware to a web-based monitoring platform via the ESP32-Cam module, which uses a Wi-Fi network to transmit data to a cloud server. Through this connection, users can remotely monitor and control devices via a web-based application hosted at the website: "monitor.simonkori.com.". A local interface is also provided via a Liquid Crystal Display (LCD) to display information. Real-time information on system parameters, such as temperature, reaction time, or pump operational status, allowing direct monitoring on site. The mechanical design of the system was created using Computer-Aided Design (CAD) software (Autodesk AutoCAD 2023 version) to ensure efficient device layout, reduce potential mechanical interference, and increase durability. With a modular design, the system can be easily adapted to larger waste management scales. The flow diagram of IoT based smart waste technology in this study can be seen in Figure 1.

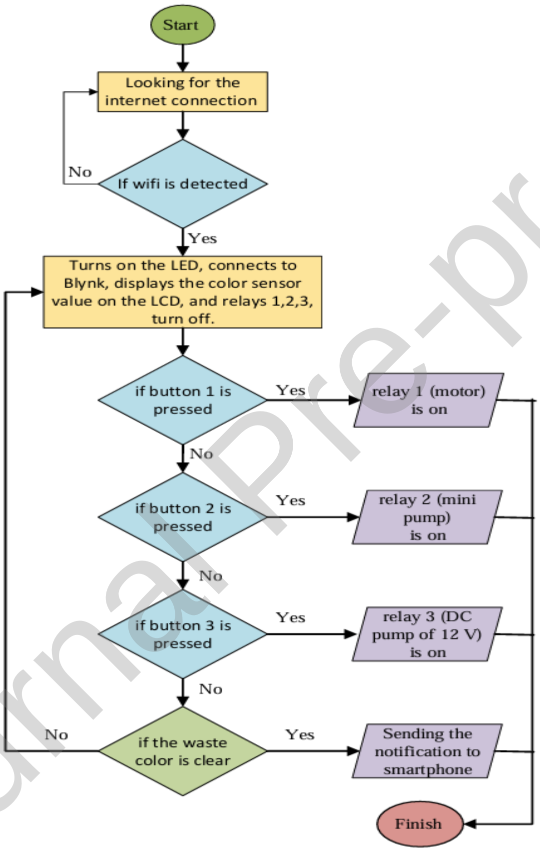


Figure 1. Flowchart of smart waste

Based on the illustrated in Figure 1, begins with system initialization to establish a Wi-Fi connection. The device continuously searches for a connection until Wi-Fi is detected. Once a connection is successfully established, an LED on the device lights up as an indicator, and the device connects to the Blynk application, enabling remote control via a smartphone. During this stage, the device also displays the waste color sensor values on the LCD screen for visual monitoring. Additionally, all relays (Relay 1, Relay 2, and Relay 3) are set to the "off" position as the default setting. After initialization, the device becomes operational and can be controlled through three primary buttons, each assigned to a specific function. Button 1, when pressed, activates Relay 1, which is responsible for starting the motor. This motor is likely utilized for mechanical processes, such as stirring or agitating wastewater solutions, to ensure the even mixing of chemicals. Button 2 activates Relay 2, which is connected to a mini pump. This pump is typically used to deliver small quantities of chemicals or water into the system as required by the process. Finally, Button 3 activates Relay 3, which is connected to a 12V DC pump. This pump is generally employed for tasks requiring larger volumes or higher pressures of water, such as transferring significant amounts of wastewater or processed liquids. One of the key features of this device is its ability to monitor the color of wastewater using a color sensor. The sensor detects the clarity level of the wastewater after it has undergone processing. If the wastewater reaches a clear condition, the system automatically sends a notification to the user's smartphone through the Blynk application. This feature enables users to monitor the status of the process in real-time without the need for direct supervision. Once all processing is complete and the wastewater is deemed clear, the system ceases operation. This device is specifically designed to enhance convenience and efficiency in waste management, particularly for batik wastewater, which often contains dyes and hazardous chemicals.

e) Dye Removal Analysis and Characterization Techniques.

The material characterization included Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM–EDX) to examine both the surface morphology and elemental composition. SEM features include the ability to generate high-resolution images (up to nanometer scale) and provide information on topography, morphology, and particle size distribution. SEM works by utilizing high-energy electrons that are fired at the sample surface. These electrons interact with atoms on the sample surface, producing signals that carry information about the topography (surface structure), morphology, and composition of the material. In this study, SEM analysis was conducted on samples containing 2% biochar and 2% zeolite. The selection of this concentration was based on two considerations. First, the 2% loading level provides representative surface characteristics that are directly relevant to catalytic performance. Second, this concentration was also used in our experimental degradation tests, ensuring consistency between the characterization and application stages. Therefore, SEM analysis at 2% loading allows us to directly correlate the observed morphology with the functional performance of the catalyst in batik wastewater treatment. The EDX detector integrated into the SEM allowed simultaneous identification of the chemical elements present. The EDX spectra confirmed the presence of major elements such as silicon (Si), aluminum (Al), and oxygen (O), which are characteristic of the aluminosilicate framework of zeolites. Minor elements such as iron (Fe), calcium (Ca), and potassium (K) were also detected, suggesting natural mineral impurities that can contribute to ion exchange and catalytic activity

The efficiency of the adsorption process is calculated using % removal parameter. This process involves measuring the initial and final pollutant concentrations, using tools such as a UV-Vis spectrophotometer for dyes. UV-Vis spectrophotometry features include the ability to measure absorbance at specific wavelengths (200–800 nm), providing quantitative information about dye concentration in solution with high sensitivity and accuracy. Dye removal analysis was conducted to evaluate the treatment efficiency for different batik wastewater colors (yellow, green, blue, red, and orange) in batik wastewater after treatment. Concentrations were determined before and after the process using spectrophotometric methods, and removal efficiency was calculated as the percentage decrease relative to initial concentrations. The degradation of dyes was assessed by calculating the percentage removal (% Removal) according to the equation:

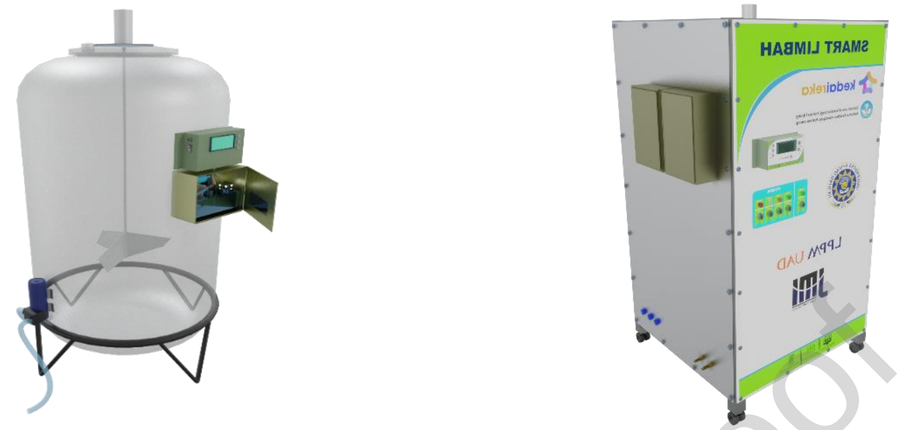
$$\text{Removal Efficiency } (\%) = \frac{(C_0 - C_e)}{C_0} \text{ x}100 \qquad (1)$$

where C0 is the initial metal concentration (mg/L) and Ce is the equilibrium concentration (mg/L) after adsorption. Dye concentrations were obtained from absorbance measurements using a UV-Vis spectrophotometer at the maximum wavelength of each dye.

Results and Discussion

a) Smart Waste Prototype for Batik Wastewater Treatment

In this study, a smart waste system was successfully developed to support the processing of liquid waste from the batik production process. The prototype design of the smart waste system consisting of several main components, including a waste processing tank, an IoT-based control module, and a circulation pump can be seen in Figure 2a. Meanwhile, the prototype design equipped with a cover can be seen in Figure 2b. The treatment tank is designed with adequate capacity to handle laboratory-scale and semi-industrial-scale wastewater. The system features a control module that integrates pH sensors, temperature sensors, and an ESP32-Cam module, which collectively gather and transmit waste parameter data to a cloud-based monitoring platform. The control module includes a local interface, represented by an LCD screen, to display operational information such as reaction temperature, process duration, and pump status. Externally, the prototype is encased in a lightweight metal shield for ensuring durability and ease of use.



a) Desain prototype smart waste b) Desain prototype with cover

Figure 2. Smart waste prototype design for batik waste

As illustrated in Figure 2, batik waste is introduced into the storage tank via the input channel. Once the waste enters the tank, the sensor system comprising a pH sensor and a temperature sensor actively monitors the waste parameters. The pH sensor measures the acidity level of the solution, while the temperature sensor ensures that operational conditions align with the requirements of the degradation process. Additionally, the system is equipped with the capability to detect hazardous pollutants based on the data collected by the sensors. If the sensor data reveals the presence of hazardous substances, such as heavy metals or organic dyes that are difficult to degrade naturally, the control module automatically activates the adsorption system to address these pollutants effectively. In this process, the waste is passed through biochar and zeolite media, which serve as adsorbents to capture contaminants effectively. Additionally, the system employs the heterogeneous Fenton method, utilizing a catalyst composed of a biochar and zeolite mixture. This method generates highly reactive hydroxyl radicals (-OH), which play a critical role in breaking down complex organic compounds into simpler, more environmentally friendly substances. Circulation pumps and gearbox motors work to ensure that the waste flow in the tank remains homogeneous during the adsorption and degradation process. Reaction parameters such as pH, temperature, and operating duration can be monitored directly via LCD or web-based application. This real-time data is also sent to a cloud server via the ESP32-Cam module, allowing users to monitor system conditions remotely. The developed prototype design provides several advantages for batik waste processing. The integration of IoT-based sensors allows real-time monitoring of critical parameters, so that operators can monitor the efficiency of waste processing without the need for manual measurements. With the support of Wi-Fi connection via ESP32-Cam, system parameter data can be accessed remotely via a web-based application, providing flexibility for users to monitor and control the system. In addition, the use of biochar and zeolite in combination with the heterogeneous Fenton method increases the efficiency in removing organic and inorganic pollutants.

a) Properties of Biochar dan zeolite

This study highlights the characteristics of biochar and zeolite as primary materials in the degradation process of batik waste, utilizing the heterogeneous Fenton method integrated into smart waste technology. As shown in Table 1, biochar exhibits a significantly larger specific surface area (SBET) of 191.825 m^2/gram compared to zeolite's 43.759 m^2/gram. The extensive surface area of biochar provides a higher adsorption capacity for complex organic compounds present in batik waste. Additionally, biochar features a micropore area (S_{mic}) of 0.854 m^2/gram, which is larger than zeolite's 0.629 m^2/gram. However, the micropore area's contribution to the total surface area is lower in biochar (0.45%) than in zeolite (1.44%), suggesting that biochar's pore structure is predominantly composed of mesopores and macropores. With an average pore diameter of 3.584 nm larger than that of zeolite (3.373

nm). biochar demonstrates greater potential for capturing complex organic molecules, making it a more effective adsorbent for the degradation of batik waste.

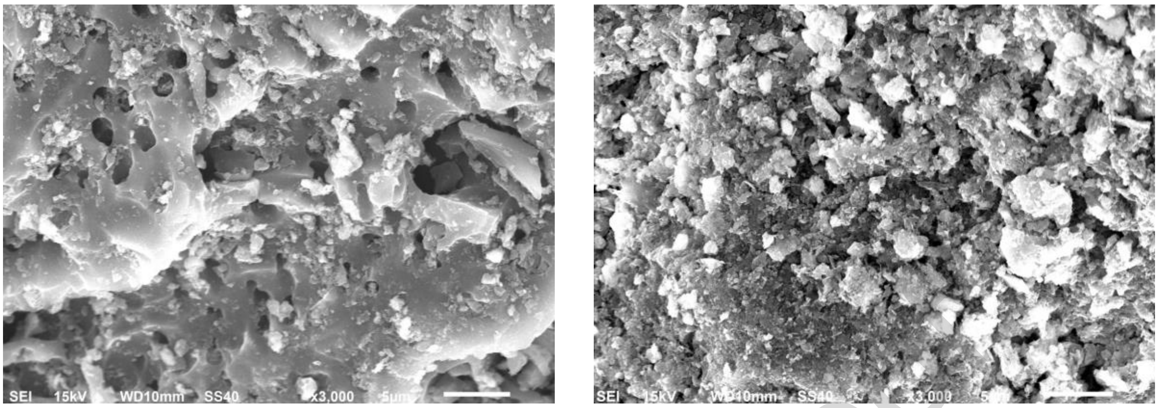
Conversely, zeolite demonstrates superiority in micropore volume, with a value of 0.058 cm^3/gram compared to biochar's 0.048 cm^3/gram. Zeolite also exhibits a higher proportion of micropore volume to total pore volume (% V_{mic}), at 37.25%, compared to biochar's 30.43%. This characteristic indicates that zeolite is more effective in adsorbing smaller molecules, such as metal ions or Fenton catalysts (Fe^{2+} and Fe^{3+}). These molecules play a critical role in enhancing the oxidation reaction efficiency in the heterogeneous Fenton method, further emphasizing zeolite's complementary role alongside biochar in the degradation process [23]. These results are in line with several previous studies that highlighted the role of biochar as an adsorbent with a high surface area. According to the research [24] Biochar, with its large surface area, is highly effective at adsorbing complex organic compounds such as dyes and phenols. Furthermore, incorporating biochar into the Fenton method enhances the efficiency of organic compound degradation by providing a robust surface for catalytic reactions and facilitating the breakdown of pollutants into simpler, more environmentally benign substances [25]. In contrast, zeolite shows that the surface area of zeolite is smaller than biochar, the micropore structure of zeolite allows the adsorption of metal ions and Fenton catalysts.

Table 1. Properties of zeolite dan biochar

Characteristic	Zeolite	Biochar
Specific surface area (S_{BET}), m^2/gram	43.759	191.825
Micropore area (S_{mic})	0.629	0.854
% S_{mic}	1.44	0.45
Total pore volume, cm^3/gram	0.156	0.157
Micropore volume (V_{mic}), cm^3/gram	0.058	0.048
% V_{mic}	37.25	30.43
Average pore diameter, nm	3.373	3.584

b) SEM-EDX Analysis of biochar

The surface morphology and elemental composition of 2% biochar and 2% zeolite were examined using Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM–EDX). This analysis aims to evaluate the morphological structure of the materials involved in the degradation of batik waste through the heterogeneous Fenton method. Figure 3a, reveals that 2% biochar exhibits a rough surface structure, featuring irregularly shaped particles of relatively large sizes. This rough and irregular morphology contributes to the material's ability to adsorb complex organic compounds effectively, making it suitable for use in waste degradation processes. This morphology reflects the characteristics of biochar as an active carbon material that has micro and mesopores, which function as active sites for the adsorption of organic substances in batik waste. This structure reflects the characteristics of biochar as an active carbon material with micro and mesopores that function as active sites for the adsorption of organic compounds from batik waste. The layered and cracked surface of biochar indicates the potential for a large contact area with pollutant molecules during the degradation process. In contrast, Figure 3b shows the surface morphology of zeolite with smaller particles and appears denser. The crystalline structure seen in zeolite supports high adsorption properties towards organic pollutants and the ability of zeolite as a catalyst in accelerating the Fenton reaction through optimal iron (Fe) distribution. The more uniform and small-porous zeolite surface also increases the efficiency of degradation of complex organic compounds. The significant morphological differences between biochar and zeolite provide complementary functions in the heterogeneous Fenton process. Biochar functions as the main adsorbent that absorbs pollutants from waste [26], [27], while zeolite acts as a catalyst that facilitates the oxidation reaction of hydroxyl radicals (-OH) [28]. The combination of these two materials is expected to optimize batik waste processing by decomposing complex organic compounds into simpler and more environmentally friendly compounds. This analysis shows that the unique morphology of carbon biochar and zeolite supports their role in the smart waste management approach, in accordance with the research objective to improve the efficiency of batik waste processing using the heterogeneous Fenton method.



a) Biochar 2% b) Zeolite 2%

Figure 3. Morphology of biochar and zeolite

The EDX results indicate that biochar (2%) is dominated by carbon (95.86%), with minor contributions from metals such as Fe, Cu, and Zn. This composition confirms the nature of biochar as a porous carbon material, while the presence of trace metals may provide additional surface functionalities and catalytic potential. In contrast, zeolite (2%) is dominated by O, Si, and Al, which form the characteristic aluminosilicate framework of natural zeolites. Minor elements such as Na, Mg, K, Ca, and Fe further enhance its ion-exchange capacity and catalytic activity, particularly in supporting heterogeneous Fenton reactions. Thus, the SEM–EDX results confirm that biochar primarily acts as a carbon-based adsorbent, whereas zeolite functions as an aluminosilicate catalyst support with intrinsic elements that strengthen its oxidative performance. The elemental composition obtained from EDX is summarized in Table 2.

Table 2. Summary of EDX analysis for biochar (2%) and Zeolite (2%)

Elements	2% of biochar (Mass %)	2% of Zeolite (Mass %)
C	95.86	8.85
O	0.85	48.12
Na	-	0.62
Mg	-	0.72
Al	-	5.11
Si	-	26.69
K	-	3.18
Ca	-	1.42
Fe	0.93	5.29
Cu	1.54	-
Zn	0.82	-

c) Adsorption performance using biochar on smart waste

The results of the biochar performance test of the smart waste system in processing batik waste are shown in Figure 4. The percentage of bicohar removal of five types of batik waste with color variations: yellow, green, blue, red, and orange. This percentage of bicohar removal shows the efficiency of the system in adsorbing and decomposing organic pollutants from batik waste through a combination of biochar and Zeolite working within the Heterogeneous Fenton Method framework. Red batik waste showed the highest removal rate of 98%, followed by orange with an efficiency of around 96%. Yellow has a removal rate of around 90%, while blue and green show lower efficiencies, around 87% and 85%, respectively. This difference can be attributed to the characteristics of the dye compounds in batik waste, including the chemical structure of the dye, its solubility, and interaction with the adsorption material and the reactivity of the catalyst in the system.

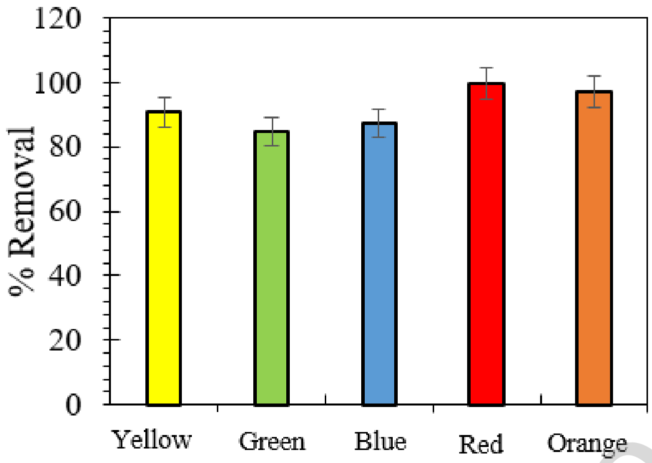


Figure 4. adsorption performance on biochar

The removal percentage seen in red and orange batik waste indicates the optimal ability of the combination of biochar and zeolite in the adsorption and degradation process using the heterogeneous Fenton method. Biochar with a large surface area and high porosity provides physical adsorption sites to capture pollutant molecules from liquid waste [29]. Meanwhile, zeolite functions as an ion exchange medium, which allows the removal of heavy metals or other ions that can interfere with the Fenton reaction [30]. In the heterogeneous Fenton method, Fe ions supported by biochar and zeolite media play an important catalytic role in producing hydroxyl radicals (-OH) through the reaction between Fe ions and H_2O_2 [31]. These hydroxyl radicals are highly reactive and are capable of decomposing complex organic compounds into simpler molecules, such as CO_2 and H_2O [32]. This reaction is influenced by the surface properties of the adsorbent. The high performance on red and orange waste can be caused by the structure of the dye which is more easily oxidized by hydroxyl radicals, while the chemical stability of green and blue dyes causes lower efficiency due to resistance to oxidation [33]. The system design also provides advantages by integrating the initial adsorption process by biochar and zeolite with the degradation reaction by hydroxyl radicals. The initial adsorption allows the concentration of pollutants on the media surface to increase, thereby increasing the degradation efficiency in the next stage. However, the lower performance on green and blue waste indicates that this system still needs further optimization, such as the addition of oxidants or adjusting the reaction pH to increase the formation of hydroxyl radicals.

d) Adsorption performance using zeolite on smart waste

zeolite adsorption performance on batik waste based on the removal percentage for five types of waste colors, namely yellow, green, blue, red, and orange can be seen in Figure 5. These results indicate that zeolite has excellent adsorption capacity with varying levels of removal efficiency depending on the type of color. Yellow, red, and orange colors show very high removal rates, each reaching 95%. On the other hand, green shows a removal rate of around 90%, while blue has the lowest removal rate, which is around 85%. The variation in dye adsorption performance in batik wastewater can be attributed to the chemical properties and molecular structure of each dye. Different dyes interact uniquely with adsorbents due to their different molecular configurations, which affect their adsorption capacity and mechanism. This is evident in studies examining various adsorbents and dyes, where differences in adsorption efficiency are attributed to the chemical structure of the dye and the presence of certain functional groups. The molecular structure of the dye, such as the chromogenic agent used in batik dyes, affects its interaction with the adsorbent. For example, naphthalene-based dyes contribute to water pollution and require special adsorbents for effective removal [34]. In addition, the absorption of dye molecules by zeolite is influenced by the structural complexity of the dye. According to [35], more complex dye structures, such as those found in blue dyes, present challenges for effective adsorption by zeolites. This complexity can hinder the interaction between the dye molecules and the zeolite pore structure, leading to lower removal efficiency. Complex dye structures, such as methylene blue (MB), have large molecular sizes and complicated configurations, which can hinder their diffusion into the zeolite pores [36]. The interaction ability of dye molecules with the active surface of zeolite is very limited. In contrast, colors such as orange and red which have simpler or more polar molecular structures tend to be more easily adsorbed [37]. The good performance of zeolite in removing color from batik waste shows its potential as an efficient material in the waste management approach using smart wastes tools. In the heterogeneous Fenton method, zeolite not only plays a role in accelerating the oxidation reaction but also contributes directly to removing complex organic compounds from batik waste. the combination of high adsorption capacity and catalytic role makes zeolite an important component in an effective and sustainable waste treatment strategy.

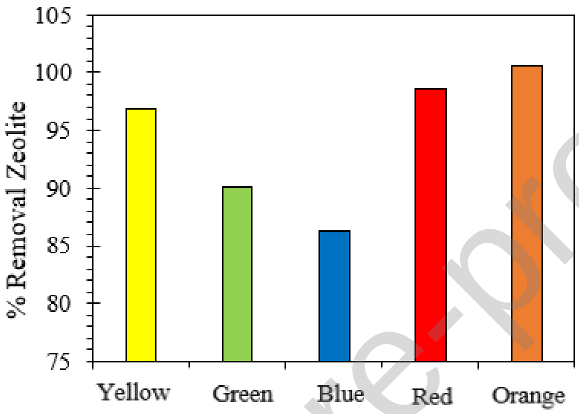


Figure 5. adsorption performance on zeolite

e) Recyclability of Adsorbents

The recyclability of zeolite and biochar was evaluated over four successive adsorption–degradation cycles, and the results are presented in Figure 6. Zeolite exhibited excellent stability, maintaining a consistently high dye removal efficiency of ~95–98% across all four cycles. This stability can be attributed to the rigid aluminosilicate framework of zeolite, which resists structural collapse during repeated use. The Si/Al ratio and the presence of ion-exchangeable cations help preserve active sites, while the well-defined porous structure prevents significant clogging. These features enable zeolite to retain its adsorption and catalytic performance even after multiple regeneration cycles. In contrast, biochar showed a drastic decline in performance with each cycle. The initial removal efficiency of ~73% in the first cycle dropped sharply to ~47% in the second cycle, ~28% in the third, and ~26% in the fourth. This rapid deactivation is mainly due to (i) pore saturation, where the porous network of biochar becomes filled with dye molecules and reaction byproducts, limiting further adsorption; and (ii) its catalytic activity being largely temporary in nature, since the reactive sites generated on biochar surfaces during initial cycles undergo degradation or are consumed in the reaction. In addition, the amorphous structure of biochar is more prone to structural changes under repeated oxidative conditions compared to zeolite’s crystalline framework. These results confirm that while biochar can function as an effective adsorbent in the initial cycle, its recyclability is limited by pore blockage and temporary catalytic reactivity. On the other hand, zeolite provides superior stability and long-term reusability, making it a more reliable material for sustainable wastewater treatment applications.

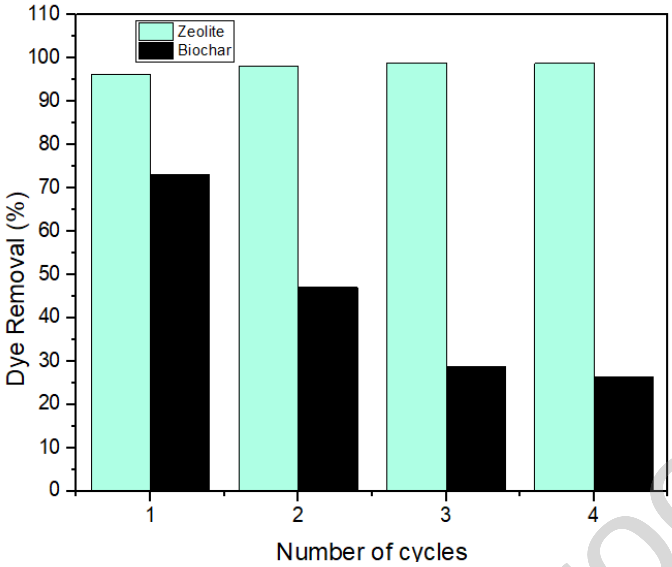


Figure 6. Recyclability of zeolite and biochar

f) Comparison with Other Adsorbents

To further evaluate the performance of the biochar–zeolite system developed in this study, its adsorption efficiency was compared with other adsorbents reported in the literature. The results are summarized in Table 3. Activated carbon derived from rubber seed pericarp biomass has been reported to achieve ~92% dye removal for methylene blue at an initial concentration of 100 mg/L and pH ~7.8 within only 10 minutes [38]. Natural Moroccan zeolite, on the other hand, demonstrated a high adsorption capacity (Qm ≈ 298.15 mg/g) depending on adsorbent weight and reaction time [39]. More advanced materials such as Fe_3O_4/zeolite nanocomposites showed even higher performance, with 96.92% dye removal and a maximum adsorption capacity of ~113.64 mg/g under optimized conditions at pH ~9 and 50 mg/L dye concentration [40]. In comparison, the biochar–zeolite system in this study achieved 95% dye removal at an initial concentration of 20 mg/L, pH 9.2, and ambient temperature (28–30 °C). This performance is highly competitive with other reported adsorbents, particularly considering that the materials used are low-cost, naturally available, and integrated into an IoT-based heterogeneous Fenton system. The results highlight that biochar–zeolite can serve as an effective and sustainable alternative for dye removal from industrial wastewater.

Table 3. Comparison with Other Adsorbents

No	Adsorbent	Condition/Initial concentration/pH/Time	Removal Efficiency	Ref
1	Activated carbon from Rubber seed pericarp as biomass	100 mg/L methylene blue, pH ~7.8, dose 0.05 g, time 10 minutes	92% dye removal	[38]
2	Natural Moroccan zeolite	variation of adsorbent weight, reaction time; initial conditions	Qm = ~298.15 mg/g (high capacity)	[39]
3	Fe_3O_4 / zeolite nanocomposite	Dye concentration 50 mg/L, pH ~9, adsorbent dose ~0.75 g/L, time ~45 minutes	Efficiency 96.92%, capacity $q_m \approx 113.64$ mg/g	[40]
4	Biochar-Zeolite (this study)	Initial concentration of 20 mg/L, pH of 9.2, temperature 28–30 °C	95% dye removal	-

Challenges and Recommendations for Future Works

The present study demonstrates the potential of IoT-integrated heterogeneous Fenton systems, yet several challenges must be addressed to ensure scalability and long-term effectiveness. Key challenges include catalyst stability and reusability, as biochar–zeolite catalysts may suffer from Fe leaching, deactivation, and reduced efficiency over repeated use. Operational sensitivity is also critical, since the heterogeneous Fenton process depends heavily on pH, temperature, and oxidant dosage; variations in wastewater composition may yield inconsistent outcomes. Sensor performance and calibration further pose challenges, as drift in pH, turbidity, or temperature sensors can reduce data reliability; strategies such as auto-calibration, redundancy, and regular validation against manual measurements are necessary. Energy and cost efficiency remain important considerations, as continuous operation of pumps and electronics increases costs; integrating renewable energy sources and optimizing duty cycles are recommended. Scalability and adoption by SMEs require addressing variable effluent loads, infrastructure limitations, and user training. Finally, regulatory and environmental considerations demand compliance with environmental standards, cybersecurity, and sustainability practices. To overcome these challenges, future work should incorporate several methodological improvements and additional controls. These include conducting multiple replicates and applying statistical analyses to validate significance, implementing blank and catalyst-only controls to distinguish adsorption from degradation effects, and comparing with a homogeneous Fenton system for benchmarking. Systematic evaluations of pH and temperature stability are necessary to optimize conditions, while reusability tests of the catalyst will clarify its long-term applicability. Periodic calibration of IoT sensors and validation against manual measurements should be carried out to ensure accuracy. Incorporating renewable energy integration, AI-driven adaptive control, and pilot-scale demonstrations in SMEs are further recommended. By addressing these issues, future research will provide stronger evidence for the performance, stability, and scalability of IoT-integrated heterogeneous Fenton processes for batik wastewater treatment.

Conclusion

This study successfully developed an IoT-integrated heterogeneous Fenton system using biochar and natural zeolite catalysts for batik wastewater treatment. The system achieved up to 95% dye removal, demonstrating strong adsorption–oxidation synergy between biochar and zeolite. Characterization results confirmed that biochar, with its high surface area, enhances adsorption of organic dyes, while zeolite, with its stable aluminosilicate framework, supports ion exchange and catalytic activity. Recyclability tests revealed that zeolite maintains high efficiency across multiple cycles, whereas biochar showed a decline due to pore saturation and temporary catalytic reactivity. When compared with other adsorbents reported in the literature, the biochar–zeolite system demonstrates competitive removal efficiency while utilizing low-cost, locally available materials. Beyond its treatment effectiveness, the integration of IoT technology enabled real-time monitoring and control, enhancing process reliability and potential scalability. Overall, this work provides a promising pathway for sustainable wastewater management in the batik industry, particularly for small and medium enterprises. Future work should focus on pilot-scale demonstrations, energy integration, and long-term catalyst stability to ensure broader industrial adoption.

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Declaration of Competing Interest

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlight:

- Smart Waste Solution Integrating IoT and Heterogeneous Fenton Process
- Biochar and Zeolite as Efficient and Sustainable Catalysts
- Integrated and Modular Smart Waste Prototype
- High Adsorption Performance on Batik Wastewater treatment
- Impact and Potential for SMEs and the Circular Economy