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Comparison of Chemical Oxygen Demand Removal Using Zeolite Adsorption and Floating Treatment Wetlands in Polluted River Water

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Abstract

The Citarum River in Bandung, West Java, provides drinking water, irrigation, and industrial resources for the local community. However, the recent increase in textile industry activity has reduced water quality, with textile waste contributing significantly to organic pollution in tropical inland waters. Addressing these environmental challenges requires treatment technologies to protect public health and the integrity of the region's ecosystem. This study aims to evaluate the adsorption performance of natural zeolite using the tea bag method (laboratory scale) and investigate its integration with a floating treatment wetland (FTW) system planted with *Canna indica* (mini-pilot scale) to reduce chemical oxygen demand (COD) under tropical environmental conditions. Batch experiments were conducted using real textile wastewater with an initial COD concentration of approximately 752 mg/L to reflect actual pollution levels. The tea bag adsorption system showed a maximum COD reduction of 43%, while the integrated FTW system achieved a higher COD reduction of 48% after 24 days of operation. The enhanced performance of the FTW system relative to the tea bag system results from the combined effects of zeolite adsorption, microbial biodegradation, and improved oxygen transfer facilitated by the *Canna indica* root system. Experimental findings indicate that the integrated FTW system offers a sustainable, cost-effective, and nature-based approach for improving water quality in tropical inland waters affected by industrial pollution. Nevertheless, additional optimization is required to achieve compliance with regulatory discharge standards.

1. Introduction

Rivers are essential freshwater resources that support human activities and aquatic ecosystems. However, increasing anthropogenic pressures have led to a decline in river water quality, particularly in rapidly industrializing regions (Ahsanul et al., 2024). Various anthropogenic activities along riverbanks can significantly degrade water quality and accelerate its decline (Anh et al., 2023; Khairuddin et al., 2019). One primary source of pollution from human activity is the textile industry. This is what happened to the Citarum River located in Bandung City, West Java Province, Indonesia (Ahsanul et al., 2024). The Citarum River has been significantly impacted by the textile industry, with thousands of textile factories lining its banks (Oktaviyani et al., 2023).

Industrial textile wastewater is a significant source of organic pollution, containing a complex mixture of chemicals, dyes, salts, detergents, softeners, acids, bases, finishing agents, and other synthetic substances that are difficult to remove. Due to these complex substances, textile wastewater often has high Chemical Oxygen Demand (COD) levels (Suyata, 2008), making treatment before discharge challenging and contributing to suspended solids and reduced water quality (Abdissa & Beyecha, 2021). Untreated textile effluents severely affect the flora and fauna in nearby freshwater bodies. This situation is of particular concern, as many textile industries still lack effective wastewater treatment prior to discharge (Khandare et al., 2013). Textile effluents, when discharged directly into freshwater bodies, deplete dissolved oxygen, negatively impacting aquatic life and human health (Haydar et al., 2011). Effective COD treatment methods are therefore essential.

Adsorption is generally considered an up-and-coming method for removing pollutants from wastewater, due to its low cost, high efficiency, and stability. Activated carbon as an adsorbent is commonly used to remove toxic pollutants from textile wastewater (Almadani, 2023), but it is also costly (Mahmoud et al., 2020). In line with this, many efforts have been made to develop effective local activated carbon from cassava peel, orange peel, bagasse fly ash, bamboo, and avocado seed (Dehghani et al., 2018; Niazi et al., 2018; Rizzo et al., 2019; Fito et al., 2019; Choong et al., 2020). However, these adsorbents present major limitations in treatment performance, preparation time, cost, regeneration difficulty, and adsorption capacity. Further investigation of adsorbents is warranted, as many are constrained by insufficient integration with biological treatment systems, highlighting the demand for more reliable and scalable alternatives. In response to these limitations and the lack of industrial-scale validation, recent research has shifted the focus from activated carbon to zeolites to identify more effective adsorbents. Zeolite and clay adsorbents exhibit higher adsorption efficiency than activated carbon, thanks to their large surface area and unique properties (Titchou et al., 2020).

Prior to zeolite being integrated into the FTWs, preliminary adsorption tests were conducted under controlled conditions to evaluate the adsorption performance. The tea bag method, applied on a laboratory scale, was used to measure the adsorbent. Although this method is not commonly used, it offers a simple, controlled approach to assess adsorption efficiency, the attainment rate of maximum capacity, and desorption potential. In the context of FTWs, persistent emergent plant most commonly Indian shot (*Canna indica*) is frequently utilized. *Canna indica* has been identified as an optimal species for application in FTWs due to its ability to tolerate a wide range of soil types and pH conditions (Bhutiani et al., 2019). Beyond its adaptability, *Canna indica* contributes to the aeration of the root zone and nutrient removal in wetland microcosms, thereby enhancing microbial activity and accelerating the degradation of organic matter (Zhang et al., 2007). Furthermore, this species increases filtration efficiency and substrate porosity through its extensive root system, thereby facilitating the uptake and sequestration of essential nutrients in plant tissues via diverse rhizosphere processes (Fraser et al., 2004), (Ramesh et al., 2017). Additionally, *Canna indica* delivers oxygen to the rhizosphere, promoting the proliferation of aerobic bacteria responsible for contaminant degradation (Yang et al., 2007; Zhu et al., 2017) and exudes root-derived compounds that serve as substrates for biofilm development (Jamwal et al., 2021). While numerous studies have investigated zeolite and *Canna indica* separately for treating industrial wastewater, focusing primarily on specific pollutants such as dyes or heavy metals (Zulti et al., 2025). Still, no research has combined the adsorption mechanism of zeolite with the FTW system using *Canna indica*.

To address the research gap, this study systematically evaluated COD removal performance using two methods in a staged approach. In the initial stage, zeolite performance was evaluated using a tea bag system. The second stage continued by integrating zeolite with *Canna indica* in the FTWs. This sequential method can demonstrate the differences between the two methods and explore the mechanistic interactions of adsorption and microbial degradation under tropical environmental conditions. To the best of our knowledge, no previous study has systematically compared preliminary zeolite adsorption performance using the tea bag method with its subsequent integration into FTWs for COD removal under tropical conditions. Therefore, the objectives of this study are: (1) to evaluate the efficiency of natural zeolite in COD removal using a tea bag adsorption system: (2) to compare COD removal performance between the tea bag system and the integrated FTW system planted with *Canna indica*: and (3) to evaluate the potential application of the integrated system as a natural-based supplementary treatment to enhance organic pollution mitigation in tropical inland waters.

2. Materials and Method

2.1 Textile Wastewater Characteristics

This research was conducted at the Testing Laboratory at the Limnology and Water Resources Research Centre, BRIN, Bogor, Indonesia, from March to July 2025. The materials used included zeolite powder, textile wastewater, and COD analyzers. Textile wastewater samples were collected from PT.X, a textile factory located in Bandung, West Java, Indonesia. The wastewater originated from the final production stage and represented the combined effluent from the entire textile process. Preliminary testing for waste characterization showed COD levels of 752 mg/L in the final production wastewater. Preliminary colour testing showed 359.1 PCU in final production waste, indicating the presence of residual dyes and organic compounds typical of textile effluents. In this test, the parameters tested were the COD parameters in the final production textile wastewater. Before use in the experiment, the final textile production wastewater was diluted to 50%. After dilution, the COD concentration was 596 mg/L; this value was used in all experiments.

The natural zeolite used in this study was obtained from Cikembar, Sukabumi, Indonesia, and was prepared to a particle size of 100 mesh prior to use.The *Canna indica* used in the FTWs was approximately 3 months old, with uniform initial heights of 40-50 cm. In the FTW experiment, *Canna indica* was first acclimatized for 50 days under controlled conditions to allow the plants to adapt to the media and environment, maximizing root integration into FTWs. All experimental treatments were repeated three times to ensure data reliability and reproducibility (triplication).

2.2. Zeolite Preparation and Tea Bag System

Natural zeolite powder wrapped in a tea bag, with a zeolite dosage of 105 g and 100 mesh particle size. These adsorption experiments were conducted in a batch system, in which the zeolite-filled tea bag was immersed in 1 L of 50% diluted final production textile wastewater in a glass beaker, with a COD concentration of 596 mg/L. During this lab-scale experiment, there was no water flow, allowing adsorption to occur under static conditions. The contact time was varied over 18 days, with sampling conducted at 0, 3, 6, 9, 12, 15, and 18 days to observe COD removal trends and determine the adsorption equilibrium time.

2.3. FTW Experimental Set-up

The FTWs included four sequential treatment configurations in a batch system, as shown in Figure 1. Each treatment was performed in triplicate. The configurations were: (i) tank K (control), with textile wastewater and an aerator but no zeolite or *Canna indica*; (ii) tank ZT, with zeolite and *Canna indica* physically separated from the zeolite, as shown in Figure 2a; (iii) tank ZsT, with zeolite integrated within the *Canna indica* root zone, as shown in Figure 2b; and (iv) tank T (plant only), with Canna indica but no zeolite.

Each tank had a capacity of 95 L and was filled with 50% diluted final-production textile wastewater, resulting in an initial COD concentration of 596.5 mg/L. The FTWs operated in batch mode without continuous inflow or outflow. Samples were collected at 0, 3, 6, 9, 12, 15, 18, 21, and 24 days to evaluate COD removal over time.

The natural zeolite used in the ZT and ZsT tanks was sourced from Cikembar, Sukabumi, with a particle size of 100 mesh and packaged in 105 g tea bags. For each 95 L tank, 950 g of zeolite was used in both ZT and ZsT tanks. In the ZT tank, zeolite tea bags were placed separately from the plant roots to allow independent adsorption. In the ZsT tank, zeolite tea bags were placed adjacent to the root zone to enable direct interaction among adsorption, root oxygenation, and microbial activity in the rhizosphere. In the FTWs, supporting parameters such as DO, temperature, pH, and salinity were also measured to control system conditions during testing.

The number of *Canna indica* plants varies by treatment: the ZT tank contains 6 plants, while the ZsT and T tanks each contain 9 plants. This aims to evaluate the potential dominance of zeolite adsorption over plant phytoremediation. Meanwhile, in the ZsT tank, the interactions between the adsorbent and plant roots during rhizosphere formation and microbial activity for pollutant degradation will be examined. This setup is expected to provide a clear distinction between adsorption mechanisms and plant mechanisms.

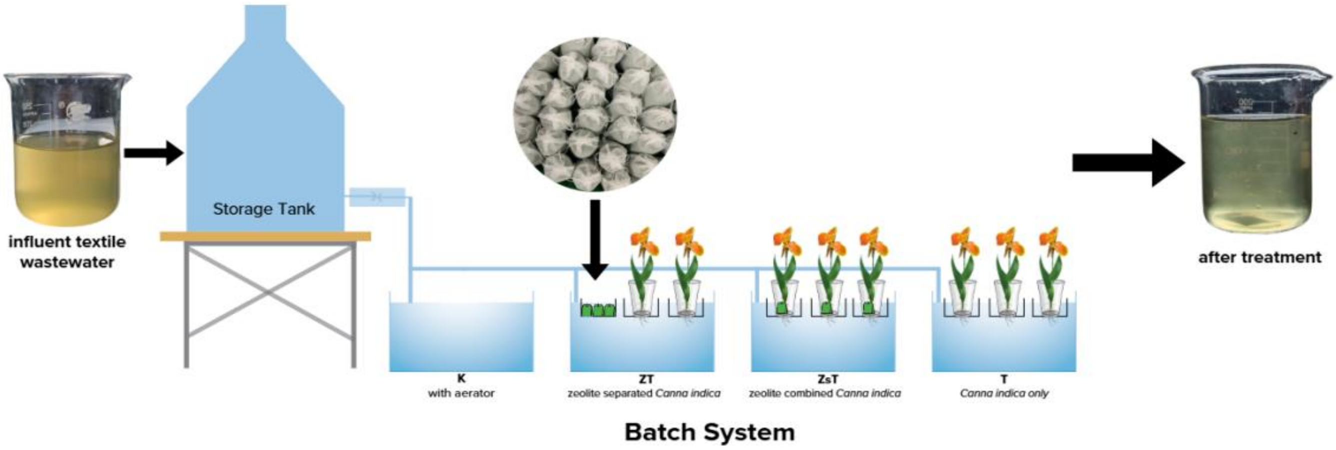


Figure 1. Graphical abstract of the experimental batch system process: from influent textile wastewater storage to the four sequential FTW treatment configurations—control (K), separated zeolite-*Canna indica* (ZT), combined zeolite-*Canna indica* (ZsT), and plants only (T)—resulting in the post-treatment effluent.

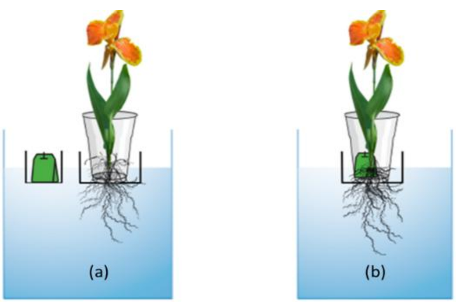


Figure 2. Structural comparison of the FTW design configurations: (a) ZT system with zeolite separated from the roots, and (b) ZsT system with zeolite integrated directly with the *Canna indica* roots.

2.4. Analytical Procedure

COD measurements were performed in the laboratory according to the Standard Method using the dichromate reflux method (APHA, 2017). All measurements were conducted in triplicate, and the average values were reported. The COD removal efficiency value after treatment can be calculated using Equation 1.

$$\%R = \frac{\mathrm{Ci} - \mathrm{Ct}}{\mathrm{Ci}} x\ 100\% \quad (1)$$

Ci is the initial COD concentration (mg/L), Ct is the COD concentration at time t (mg/L), and %R represents the COD removal efficiency.

2.5. Data Analysis

Test results were analysed using descriptive statistics, including mean values and SD, to evaluate trends in COD removal efficiency, adsorption capacity, and changes in tropical environmental parameters (pH, temperature, dissolved oxygen, and salinity). Differences among FTWs variations (K, ZT, ZsT, and T) were assessed using ANOVA. To compare the COD removal performance between the tea bag and FTW systems, an independent t-test was used.

3. Results and Discussion

3.1. COD Reduction Using Zeolite in the Tea Bag System

The effect of contact time on COD removal from textile wastewater using the tea bag method with zeolite is shown in Figure 2. The COD concentration decreased with increasing contact time until the sixth day. The COD concentration decreased from 596.5 mg/L to 345.75 mg/L, resulting in a removal efficiency of 33%. However, the concentration increased again on the 9th day, after which the removal efficiency decreased. The graph shows that the zeolite is most effective until the 9th day. This phenomenon was statistically significant (*$p < 0.001$*), indicating that zeolite has a limited adsorption capacity (Castro et al., 2021). Although efficiency increased again on day 18 (43%), this unstable trend underscores the need for more sustainable system integration. In addition, the absence of oxygen or anaerobic conditions in the tea bag system results in zeolite saturation due to the lack of natural biological regeneration (Skouteris et al., 2020).

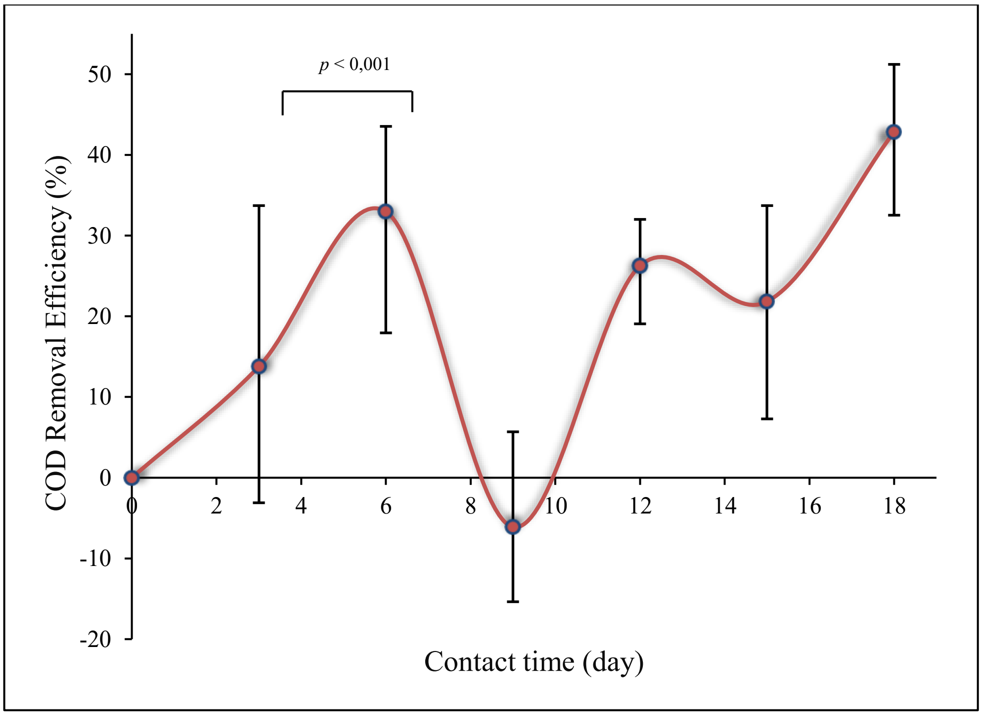


Figure 3. COD reduction trend over contact time and removal efficiency

Although dissolved oxygen was not directly measured in the tea bag system, the absence of aeration suggests that the system may have operated under oxygen-limited conditions. Therefore, the tea bag system was combined with an integrated FTW system for *Canna indica* plants, and an aerator was added to the K tank. This is consistent with the literature (Zhang et al., 2026), which indicates that aeration can increase system efficiency and improve organic biodegradation and treatment effectiveness. Another variation in the FTW system provides dissolved oxygen to plants through photosynthesis in leaves and through the diffusion of atmospheric oxygen (Stefanakis & Tsihrintzis, 2012).

3.2. COD Reduction in Zeolite–*Canna indica* Integrated System

This is the result of textile wastewater treatment using an integrated FTWs with zeolite and *Canna indica* plants. Figure 3 shows the system's degradation rate as a function of COD concentration and contact time. The initial COD concentration of 596.50 mg/L became 437 mg/L in tank K, 242 mg/L in tank ZT, 286 mg/L in tank ZsT, and 322 mg/L in tank T significant interaction *($p = 0.167$)*, indicating consistent trends across treatments. Over the 24-day testing period, FTWs produced varying COD reduction efficiencies across treatments. The ZT tank achieved the highest removal efficiency RE at 48% on day 24, followed by the ZsT tank at 37%, the T tank at 30%, and the K tank at 16%. *Two-Way ANOVA* confirmed that COD reduction was significantly affected by contact time and treatment type *($p < 0.001$)*, with no

In the ZT tank, zeolite separated from the root zone creates a more favorable microenvironment for COD degradation. The mechanism in this tank begins with zeolite adsorption, which serves as the primary COD removal mechanism, while *Canna indica* rhizofiltration regenerates the system over a longer timescale. The zeolite surface provides a surface for microorganisms to form a biofilm. Separation from the roots prevents nutrient competition, allowing the zeolite to form a stable biofilm for COD biodegradation (Ho et al., 2024). However, in the ZsT tank, competition occurs between organic compounds and plant roots for nutrients (Yugi Prasetyo et al., 2024).

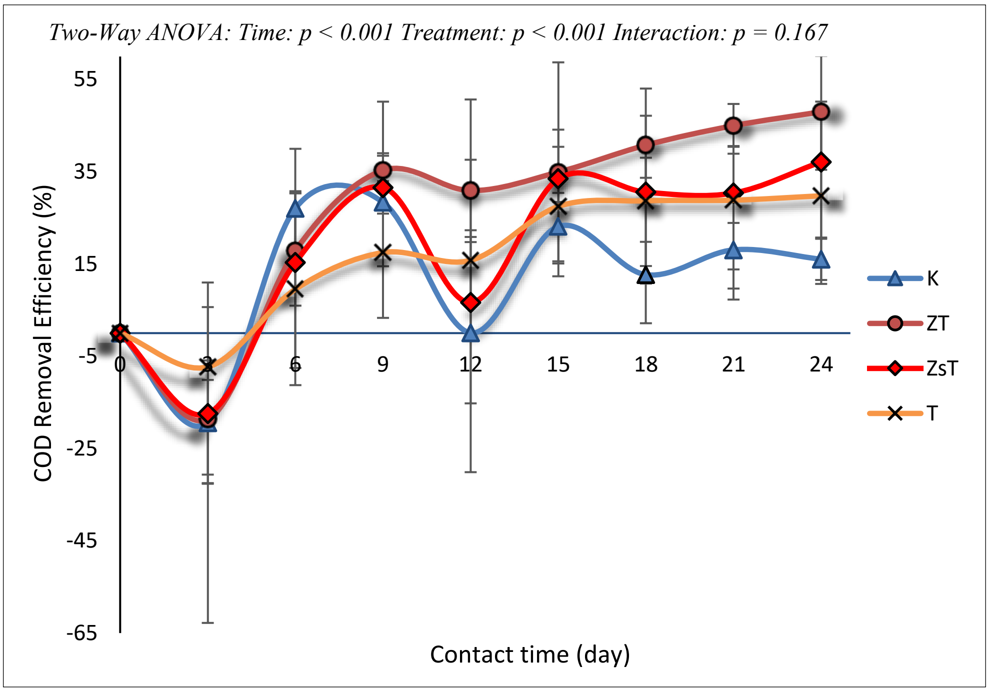


Figure 4. COD removal efficiency trend over contact time.

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

Figure 5. Top-view images of the four sequential treatment configurations during the batch experiment: (a) K tank, (b) ZT tank, (c) ZsT tank, and (d) T tank.

Zeolite binds nutrients such as NH4+ and reduces their availability to *Canna indica* roots. Biofilms develop on the zeolite surface and in the root environment, spreading their formation. This also triggers a decrease in their dynamic concentration. This scattered formation inhibits optimal COD biodegradation, emphasizing the importance of separating the zeolite-root zone to minimize biofilm dispersion (Malakar et al., 2023). The temporal variation of COD removal efficiency observed in all treatment configurations is presented in Figure 4. The role of *Canna indica* plants in the ZT and ZsT tanks is evident in their roots. *Canna indica* provides an area for microorganisms to grow, reduces pollutants in wetland systems, and creates highly aerobic conditions (Sharma et al., 2014). Visual observations of the four treatment configurations at the end of the batch experiment are shown in Figure 5.

3.3. Comparative Analysis and Mechanism Interpretation

Based on processing results using a tea bag system with an integrated FTW system, the data show that both can reduce COD pollutants in wastewater with varying levels of efficiency. The comparison data are shown in Table 1, using data from the FTW system for one of the treatment variations, namely ZT.

Table 1. Comparison of removal efficiencies (% Removal at (t15) and highest RE) and statistical significance between the tea bag substrate and the FTW (ZT tank) systems.

System	% Removal (t15)	Highest RE	Statistical Comparison
Tea bag	-6%	43%	
FTW (ZT Tank)	31%	48%	*p = 0,046*

Table 1 above shows the results of textile wastewater treatment using the tea bag method (zeolite adsorption) and the integrated FTW system with *Canna indica*. An independent t-test with unequal variances was used to compare the tea bag method and the FTWs (ZT Tank) at t=15. The FTW system demonstrated a significantly higher removal efficiency (31.97%) than the tea bag method (–5.28%) ($p = 0.046$), which suggests superior and more consistent treatment performance. Given that testing of zeolite tea bags and FTW was conducted simultaneously, their removal efficiency values could be compared on the 15th day of testing. On the 15th day, zeolite tea bags reduced COD by -6%, while FTW (ZT Tank) achieved a removal efficiency of up to 48%. This indicates a difference between zeolite in the tea bag method and zeolite integrated with *Canna indica* in the FTW system. The zeolite adsorption process plays a role in reducing organic matter, in line with research conducted by (Ojstrsek & Fakin, 2011). The highest RE values achieved by each system were 43% and 48% for teabags and FTW (ZT Tank), respectively. Several processes contribute to reducing organic matter, including biodegradation by microorganisms in the media and root zone, as well as assimilation by plants (Trifando et al., 2022). Waste treatment in the FTW system integrated with zeolite adsorbents also depends on plant roots and microbes. According to J. Zhang et al. (2014), under both aerobic and anaerobic conditions, organic matter is removed by bacteria and other microbes. Submerged plant roots provide a rhizosphere that supports the degradation rate of organic compounds by microbes. Plant activity enhances synergy with zeolite adsorption during aerobic COD degradation. Additionally, high oxygen transfer in the system aids the nitrification process and organic waste removal (Liang et al., 2017; Hdidou et al., 2022). Plants act as areas that provide rhizomes, which serve as containers for microorganisms to grow. Radial Oxygen Loss (ROL) facilitates the transfer of oxygen to the rhizosphere, thereby enhancing nutrient absorption. The root system plays a vital role in transferring oxygen from the leaves to the roots. Oxygen is obtained from the air through photosynthesis, then transported through the aerenchyma in plants to the roots and the rhizosphere (Trifando et al., 2022).

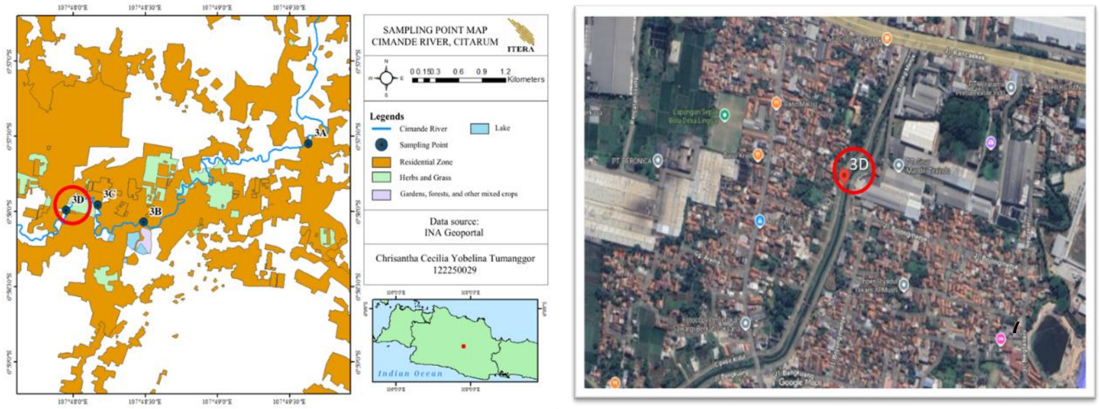
In general, plants used in wetlands in tropical and intertropical regions are macrophytes characteristic of natural wetlands, such as *Phragmites australis* and species of *Typha, Scirpus,* and *Cyperus* (Sandoval et al., 2019). However, ornamental vegetation is a promising alternative due to its aesthetic and commercial value, among which the *Canna* species stands out (Sandoval et al., 2019; Tejeda et al., 2022). *Canna indica* plants in the FTWs play a role in supplying oxygen through the intercellular space, known as aerenchyma. Research (Li et al., 2013) explains that aerenchyma functions to channel oxygen from the air to the leaves, stems, and roots/rhizosphere. Many microorganisms utilize dissolved oxygen in the rhizosphere to degrade organic matter. Photosynthesis also plays a role in supplying oxygen from the leaves to the roots. Increased dissolved oxygen makes the system more aerobic, which in turn increases the rate of degradation by microorganisms both in the root zone and on the adsorbent. Sufficient oxygen supports the decomposition of organic matter and the metabolism of microorganisms (Trifando et al., 2022). Research (Li et al., 2013) also shows that microorganisms break down organic matter into simpler forms that plants can then utilize as nutrients. Microorganisms can decompose organic matter because they have specialized enzymes during metabolism that break it down into simpler forms. Microorganisms decompose organic matter to produce energy, synthesize cellular components, respire, and move (Hammer & Mark J. Hammer Jr., 2014).

3.4. Application Potential in Indonesian Tropical Waters

As a consideration for potential application in Indonesian tropical waters, one example of COD levels in the Citarum River, in Bandung, West Java, was taken specifically in a tributary, namely the Cibodas River (Fig. 6). This concentration falls within the range of previous studies, which reported values of 114-610 mg/L (Sumantri & Rahmani, 2020).

Data collection was conducted at several monitoring stations along the Citarum River watershed, as presented in Figure 6a. Among these stations, point 3D was selected for COD analysis and detailed assessment due to its proximity to industrial activities. Figure 6b provides a high-resolution satellite view of the sampling location, illustrating the surrounding industrial facilities and the river's visual condition, thereby providing additional field-scale context for interpreting water quality conditions. This visual evidence (b) complements the spatial distribution map shown in (a) and supports selecting site 3D as a representative location for COD assessment.

The concentration in the Cibodas River, 397 mg/L, was close to the textile waste concentration used in this test, with an average of 475 mg/L per tank. As an innovative treatment method, the COD reduction achieved by the FTW system demonstrates potential for application in additional in-situ treatment.

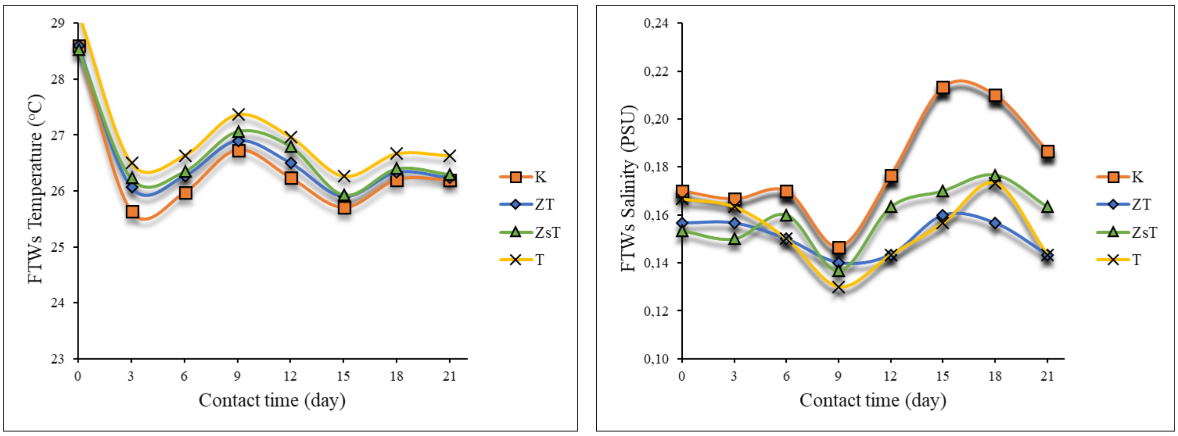


(a) (b)

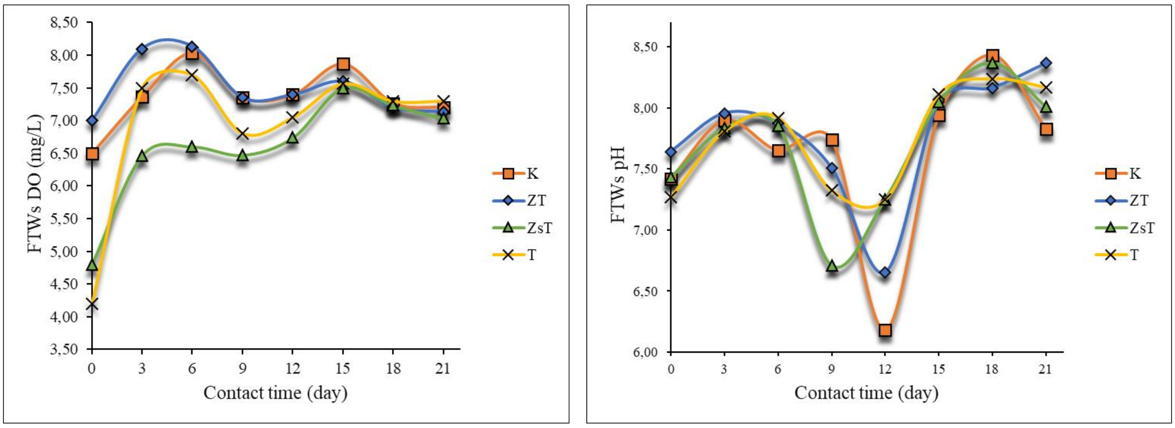
Figure 6. (a) Location of sampling sites (3A–3D) along the Cimande River and surrounding land-use characteristics. (b) High-resolution satellite image showing the exact location of sampling site 3D selected for detailed field observation and water quality assessment.

The FTW system reduced COD concentrations to 242 mg/L, achieving a 48% removal efficiency. Although this value does not meet the water quality standard of 150 mg/L (PermenLHK No. 14 Tahun 2019 tentang Baku Mutu Air Limbah Industri Tekstil), it represents a significant reduction in the organic load. For polluted river waters such as the Cibodas tributary, COD reduction is an important first step in restoring dissolved oxygen levels and improving ecological conditions. The tributary estuary also has low hydraulic conductivity, which supports prolonged contact between the polluted water and the roots of FTW plants (such as *Canna indica*), increasing COD rhizofiltration efficiency before pollution spreads to the main river (Yang et al., 2022).

Therefore, the FTW system can be positioned as a treatment technology, implemented in strategic locations such as tributary estuaries, industrial discharge points, or low-flow river sections to reduce pollution before it is transported further downstream. This shows that the results of this FTW system test have the potential to be applied on a field scale in Indonesian waters with tropical characteristics. This wetland treatment is promising, robust, and compact in tropical climates (Trein et al., 2019) compared to non-tropical regions (Molle et al., 2005). Figure 7 shows graphs of pH, temperature, DO, and salinity as an overview of the climate during the FTW testing.



(a) (b)



(c) (d)

Figure 7. Water quality fluctuations as a function of contact time in the batch FTW systems: (a) temperature, (b) salinity, (c) dissolved oxygen (DO), and (d) pH profile.

The temperature in the ZT tank showed no significant day-to-day differences, decreasing only on the third day of data collection from 29 °C to 26 °C. Consistent with the increase in RE observed at t = 9 in the ZT tank (Figure 3), the temperature increased from 26 °C to 27 °C. High temperatures enhance enzymatic activity and accelerate the biodegradation of organic matter (Wang et al., 2021). DO level remained relatively stable at 7-8 mg/L. This condition aligns with the sustained COD removal observed in the FTWs, particularly in the ZT tank, where DO levels were relatively stable compared to the other tanks (ZsT, T, K). This supports the ZT tank's superiority over other tank variations in COD degradation. Adequate DO supports microbial degradation and prevents anaerobic conditions that can lead to COD desorption, as observed in the tea bag system. Consistent DO levels indicate effective oxygen transfer and are essential for ongoing biodegradation (Murti et al., 2021). pH ranged from 7 to 8, which is optimal for microbial activity and zeolite adsorption. Previous studies have shown that biodegradation efficiency increases significantly at pH values above 7.0 (Ado et al., 2025). This aligns with findings at pH on t = 12. Decreasing the pH to pH = 6 resulted in a decrease in RE in all tank variations. Acidic pH can inhibit microbial-assisted COD degradation because the microbial community involved in organic matter degradation is more active under neutral to slightly alkaline conditions (Rohim et al., 2015). Plants and microorganisms in wetlands require a pH between 6 and 8 to support the biochemical processes that transform and degrade contaminants (Monteagudo-Hernández et al., 2024). The water salinity levels were relatively low, ranging from 0.14 to 0.17 ppt, indicating a biological balance between microbes and plants in the system, with both actively participating in degradation. Increasing salinity is expected to reduce the efficiency of organic matter removal (Frank et al., 2017). This is evidenced by the finding that increasing salinity levels in the ZsT tank at t=18 were accompanied by a decrease in RE COD (Figure 5). Under high salinity conditions, microbes experience metabolic disruption due to cell shrinkage, resulting in a decreased rate of pollutant degradation (Zhang et al., 2023). Temperature, pH, DO, and salinity are factors that need to be considered if this system is to be applied on a field scale, in situ treatment of tropical climate waters.

Given the environmental characteristics of the study area, the FTW system shows potential for future application and scale-up in direct river water treatment. The tropical climate provides favorable conditions that enhance plant growth and stimulate microbial activity, both of which are essential for effective pollutant degradation. High sunlight exposure maintains warm water temperatures, which in turn support synergistic processes such as adsorption, biofilm formation, and rhizofiltration. It is also important to emphasize that the textile wastewater used in this study originated directly from an industrial outlet rather than being synthetic wastewater, which likely increased the treatment challenge due to its more complex and variable composition.

Although this study focused on textile wastewater treatment, the system could also treat other types of wastewaters. The treatment mechanisms occurring in FTWs, such as zeolite adsorption and rhizofiltration, demonstrate potential applications for wastewater treatment that also contain organic matter. Previous studies have reported successful applications of FTW systems for municipal wastewater treatment (Faulwetter et al., 2011), aquaculture wastewater treatment (Rehman et al., 2019), and agricultural runoff management (Spangler et al., 2019), all of which contain organic matter, supporting the broader relevance of this approach. However, the efficiency of an integrated FTW system for other types of wastewaters will depend on the wastewater's characteristics, such as salinity, nutrient content, acidity level, and other specific characteristics (Oliveira et al., 2021). Therefore, FTWs is best positioned as a treatment or post-treatment option for wastewater containing organics, particularly in tropical regions, as it supports the biological processes within the system.

4. Conclusion

This study demonstrates the adsorption capacity of zeolite on tea bags and its integration with an FTW using *Canna indica* to reduce COD levels in textile wastewater. The highest RE value in the tea bag system was 43% via direct adsorption, and in the FTW system, it was 48% in the ZT treatment tank, with a final COD concentration of 242 mg/L. However, the final treatment results do not meet industrial wastewater quality standards. Therefore, further optimization of the FTW system's wastewater treatment is needed. Despite these limitations, the findings indicate that zeolite-integrated FTW has potential for application in tropical river environments, where adsorption, rhizofiltration, and microbial processes contribute to pollutant degradation. For field-scale applications, optimizing zeolite dosage, adjusting contact time, and increasing wastewater flow rate are required. Future studies should also evaluate other textile wastewater parameters, such as color, TSS, and ammonium, to ensure a comprehensive assessment of treatment performance. Overall, this study provides initial evidence on the feasibility of zeolite-integrated FTW and sheds light on the development of effective, nature-based, and scalable wastewater treatment solutions.

5. Data Availability Statement

The data included and used in this study are not confidential and are available upon request.

6. Funding Institutions

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7. Conflict of Interest

Every author has stated that there is no conflict of interest to the manuscript's writing or submission.

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9. Author Contribution

FZ contributed to the conceptualization of the study, manuscript outline, and review of the manuscript. **RN** contributed to data analysis, graphical interpretation, and review of the manuscript. **CC** conducted experimental work, performed data analysis, prepared figures, and drafted the manuscript. All authors read and approved of the final manuscript.

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