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Eco-friendly solutions for urban wastewater: evaluating constructed wetlands and filtration methods

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ABSTRACT

Urban domestic wastewater is characterized by high concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS), which pose significant environmental risks. This study aims to evaluate the effectiveness of constructed wetlands (CW) and filtration methods as biological pre-treatments to reduce these pollutants. Three reactors were employed: two types of CW using water bamboo (Equisetum hyemale) and water jasmine (Enchinodorus palifolius) and a filtration unit without plants utilizing sand and gravel as media. This design facilitated a comparative analysis under controlled laboratory conditions. The filtration method demonstrated superior performance in reducing BOD, COD, and TSS compared to the CW setups. Although all methods surpassed the quality standards set by regional regulations, filtration showed a higher removal efficiency, especially for TSS, which was effectively trapped in the filter media. The study highlights the differential capabilities of plant-based systems versus physical filtration in treating urban wastewater. While all tested systems effectively reduced pollutant levels below the mandated standards, the integration of filtration systems offers a more consistent and higher efficiency, particularly for TSS removal. These results underscore the potential of combining biological and physical treatment processes to enhance urban wastewater management strategies.industrial and agricultural pollutants, improving water quality sustainably and cost-effectively.

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1. Introduction

The increasing global population, the scarcity of freshwater resources, and the proliferation of domestic wastewater have emerged as pressing global concerns in recent years [1-2]. An estimated 1.2 billion people worldwide lack access to potable water, and nearly two-thirds of the global population grapples with water scarcity annually [3-4]. A substantial portion of the wastewater generated by human activities has pollutant characteristics such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), etc. This domestic wastewater is generally untreated and discharged directly into rivers, thus threatening water quality. Therefore, it is essential to enhance the quality of water, reduce contaminants, and promote wastewater recycling and reuse in both rural and urban areas by 2030, as per Sustainable Development Goals (SDGs) 6 [5-6]. Because of its intricate nature, domestic wastewater remains a compelling area for investigation. Under certain circumstances, untreated wastewater from other sources may be toxic and hazardous. In urban areas, untreated wastewater is discharged directly into water bodies, resulting in declining water quality. Rivers and other water bodies are limited in accommodating pollutant loads from various sources, including industries, hospitals, and offices [7-8].

Researchers have developed an extensive array of domestic wastewater treatment technologies. Recent studies have focused on decentralized approaches, emphasizing the utilization of natural treatment methods, such as constructed wetland (CW) technology or aerobic and anaerobic biological treatment systems [6, 9]. CWs have been extensively applied to various wastewater treatment scenarios. CW technology is typically incorporated in the third or final stage after pretreatment and primary treatment in industrial wastewater treatment with high effluent characteristics. However, in rural or urban wastewater treatment systems with land constraints and simplified operation, CW is sometimes employed as the primary treatment method [10-12]. CWs represent one of the most effective nature-based solutions for enhancing wastewater treatment efficiency, offering significant sustainability potential when designed and operated appropriately. Moreover, this technology is cost-effective, as it leverages the natural environment, necessitating only diligent care and knowledge [13].

CW has demonstrated high removal efficiency for contaminants in both lab-scale and field settings. CW systems have to consider the interrelationships among water, energy, and the environment to ensure sustainability and efficiency. The majority of research on CW has focused on the design, flow patterns, contaminant removal efficiency, and underlying mechanisms. However, it is necessary to expand the scope of CW applications and improve their efficiency. This can be achieved by broadening the design criteria and enhancing or modifying the component efficiency [13-15]. CW technology combined with filtration methods presents a potential solution for addressing the challenges in urban domestic wastewater treatment by leveraging the advantages of integrating two processes within a single unit. However, it is important to consider the drawbacks of combining these technologies into one operating unit, such as increased energy consumption and higher operational costs.

The primary objective of this research was to assess the effectiveness of various operating modes of CW and filtration technologies as biological pre-treatment methods for reducing the pollutant load in urban domestic wastewater. The study involved three distinct modes of operation: CW1 (mode 1) utilizing water bamboo plants (Equisetum hyemale), CW2 (mode 2) using water jasmine plants (Enchinodorus palifolius), and employing filtration (mode 3). The planting media utilized in CW1 and CW2 were the same as those used in mode 3, consisting of sand and coral. The primary objective was to remove BOD, COD, and TSS from the urban domestic wastewater. By contrasting the outcomes of the different operation modes, this study identified the most effective approach for biological pre-treatment. Overall, all three operation modes effectively reduced BOD, COD, and TSS contaminants.

2. Materials and methods

2.1. Schematic of the experimental

The implementation of a CW research device system at the Environmental Engineering Laboratory of Universitas PGRI Adi Buana Surabaya has been documented. Figure 1 shows a schematic of the CW system. Initially, wastewater was pumped into a 200 L holding tank and then directed to each CW reactor and filtration unit using a continuous flow system with a flow rate of 10 L/day for each reactor unit. For wastewater treatment, three reactors made of 4 cm thick acrylic material with identical dimensions (L × W × H = 60 cm × 30 cm × 35 cm) were utilized, providing a total wastewater volume of 45,000 cm^3. In CW1, water bamboo (Equisetum hyemale) was used as the planting medium, and CW2 incorporated water jasmine (Enchinodorus palifolius). Reactor 3 employed a filtration system with sand (ϴ ±0.08 cm) and coral (ϴ ±2 cm) as the media, with each layer having a thickness of 12 cm.

The laboratory-scale experimental reactors were designed with the same influent and operated under different conditions. Prior to entering the main treatment section, which included CW and filtration, the wastewater flowed through an empty space (down-flow). Next, the water flowed to the main treatment (CW and filtration) through the pipe at the bottom towards the top (up-flow). The separation of empty spaces from the main treatment section was intended to prevent the media from being transported along with the treated water flow. To ensure the even distribution of water within the reactor, small holes were incorporated at the bottom, and broom fibers were used to separate the sand and coral media to prevent mixing. Valves were installed to maintain a constant and controlled flow rate in each reactor.

2.2. Characteristics of domestic wastewater and research setting

The domestic wastewater samples used in this study were obtained from drainage channels situated in the Dampa'an village, Cerme sub-district, Gresik district, East Java. Figure 2 illustrates the sample point in this study. Generally, the village residents discharge their domestic wastewater into the drainage network without pre-treatment. The initial characteristics of domestic wastewater to be treated are summarized in Table 1. Cerme sub-district, Gresik district, East Java, and the condition of domestic wastewater used as a sampling site.

Samples were collected from domestic wastewater at the primary drainage channel, where residents typically dispose of wastewater. The domestic wastewater was characterized as grey-black and did not emit a strong odor. This could be attributed to periodic rainfall during the research period, which slightly diluted the wastewater with rainwater. Measurements were taken in the field using a portable device to determine the temperature and pH of the wastewater before it was transferred to the CW reactor. The results showed that the average temperature of the domestic wastewater in the drainage network ranged from 28.6-29.0 ℃, with an average pH of 6.4.

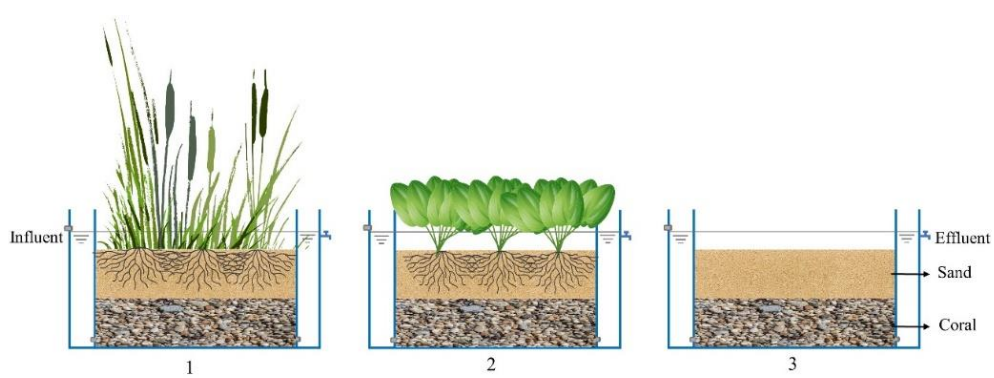

Fig. 1. Schematic illustration of constructed wetland (CW) and filtration modes: (1) water bamboo (Equisetum hyemale), (2) water jasmine (Enchinodorus palifolius), (3) filtration (sand and coral).

Fig. 2. Illustration of Google Earth for Dampa'an village

Table 1. The initial characteristics of the domestic wastewater.

Parameter	Quality standard [16]	Value
BOD (mg/L)	30	193.71
COD (mgO_2/L)	50	445.08
TSS (mg/L)	50	312.00
pH	6.0 - 9.0	6.6

Examination of raw domestic wastewater revealed that it exceeded the established quality standards. This finding illustrates the highly polluted nature of the domestic wastewater in the sampled area, posing a threat to the aquatic ecosystem and the environment. High pollutant levels primarily stem from the dense population in the region, which discharges wastewater directly into the environment. Furthermore, a substantial number of residents engage in home-based industrial activities such as laundry services, food establishments, motorcycles, and car washing workshops. These businesses contribute to increased domestic wastewater volume and heightened pollutant parameters. The treatment objectives for wastewater align with the guidelines outlined in East Java Governor's Regulation No. 52 of 2014 [16]. Prior research conducted in the urban village of Gebong Surabaya reported initial concentrations of 186.24 mg/L for BOD, 352 mg/L for COD, and 400 mg/L for TSS [2].

2.3. BOD, COD, and TSS procedures analysis

The analysis of BOD and COD pollutants followed the guidelines set by Indonesia National Standard SNI-6989.72.2009 [17], while the analysis of TSS adhered to the standards outlined in SNI-6989.3.2019 [18]. For BOD analysis, water samples were stored for five days at 20°C, without light, and sealed for BOD_5 analysis. Two samples were taken: one to determine the initial amount of oxygen (O_2) and the other to measure BOD at the end of the study time. BOD_5 is expressed in mg/L of oxygen and helps assess the impact of effluents on the environment. At the same time, COD testing involves using strong oxidizing reagents such as potassium dichromate ($KMnO_4$) to measure the amount of material that can be oxidized. COD values are expressed as the mass of oxygen consumed per unit volume (mgO_2/L). This test helps determine the impact of effluents on the environment and is essential for assessing water quality. On the other hand, TSS analysis involves passing a volume of sample through a membrane filter and then drying the filter in an oven at 105°C to determine the weight of suspended solids. TSS is measured in mg/L and is a key parameter for assessing wastewater quality.

2.4. Data analysis method

In the laboratory, wastewater samples from both the influent and effluent were collected and analyzed periodically to evaluate the performance of CW and filtration in removing BOD, COD, and TSS contaminants. This study was conducted over a period of five days and showed the highest level of accuracy. The efficiency values for all the measured parameters were calculated using Eq. 1 [19-20]. The obtained data were processed using Origin Pro 2024 software (Origin Lab Corporation, Northampton, MA, USA).

Removal ratio (%)ε =

$$\frac{C_{0\,-\,C}}{C_0} \times 100 \qquad (1)$$

where ε is the efficiency, C_0 is the initial concentration, and C is the final concentration.

3. Results and discussion

3.1. The mechanism in the constructed wetland (CW) and filtration system

A CW is a physical structure that resembles a canal and is characterized by its impermeability and the presence of wetland plants. CW systems may or may not contain filter media, thus providing an appropriate environment for plant growth. Plants in CW systems, such as macrophytes, facilitate the transfer of ambient oxygen to the substrate, promote the growth of microorganisms around plant roots, and aid in the decomposition of wastewater [21]. Numerous experiments have demonstrated the effectiveness of CW in reducing various contaminants, including BOD, COD, TSS, total dissolved solids (TDS), total nitrogen (TN), total phosphorus (TP), heavy metals, pesticides, antibiotics, personal care products, and oils. The primary mechanisms involved in pollutant removal within CW systems include biochemical transformations, adsorption, precipitation, volatilization, and uptake of pollutants by plants, as depicted in Figure 3 [22]. These mechanisms involve physical, chemical, and biological processes, targeting specific contaminants in each process while also considering various factors that influence the overall efficiency [13].

The mechanisms within the CW process are designed to improve the quality of water, considering its inherent variability and interconnected nature. CW systems are constructed to provide a sustainable means of treating polluted water, requiring minimal operation and costs. This cost-effective and technically feasible approach not only effectively treats wastewater but also contributes to aesthetic improvements while enhancing the overall wastewater removal efficiency.

Wastewater treatment through filtration involves two primary mechanisms: particle filtration and membrane filtration. Particle filtration is aimed at removing particles of various sizes from a liquid. For this purpose, a range of filters have been used, including sand, cartridges, corals, bags, and membrane filters. These filters not only facilitate particle removal but also create a favorable environment for microorganisms that aid in the decomposition of contaminants present in wastewater. As the wastewater containing particles passes through the filter, they are captured within the filter media, and the microorganisms attached to the filter media break down the wastewater as part of their survival process. The selection of the filter media depends on the initial condition of the wastewater entering the treatment system and the desired level of purification for reuse after the filtration process [23-24].

3.2. Plant acclimatization

The process of plant acclimatization is undertaken to facilitate the plants' adjustment to their new environment. This process entails monitoring the plants for several days until new shoots emerge in the CW plants. The initial stage of acclimatization involves gradually transitioning from watering the plants with fresh water to using domestic wastewater.

The appearance of new shoots during the acclimatization process indicates that the plants have successfully adapted to their new environment, indicating that the CW system is ready for operation [12]. In this particular study, water bamboo exhibited new shoot growth on the ninth day, while water jasmine showed new shoot growth on the seventh day, as depicted in Figure 4.

3.3. Temperature and pH value in the reactor

Accurate monitoring of pH and temperature is paramount in wastewater treatment processes. This information is crucial for determining the optimal level of bacterial activity, maximizing biohydrogen production, and ensuring a highly effective treatment process [25]. In this study, daily measurements of the pH and temperature in each reactor were conducted. Figure 5 depicts the observed trends in the pH and temperature throughout the study period.

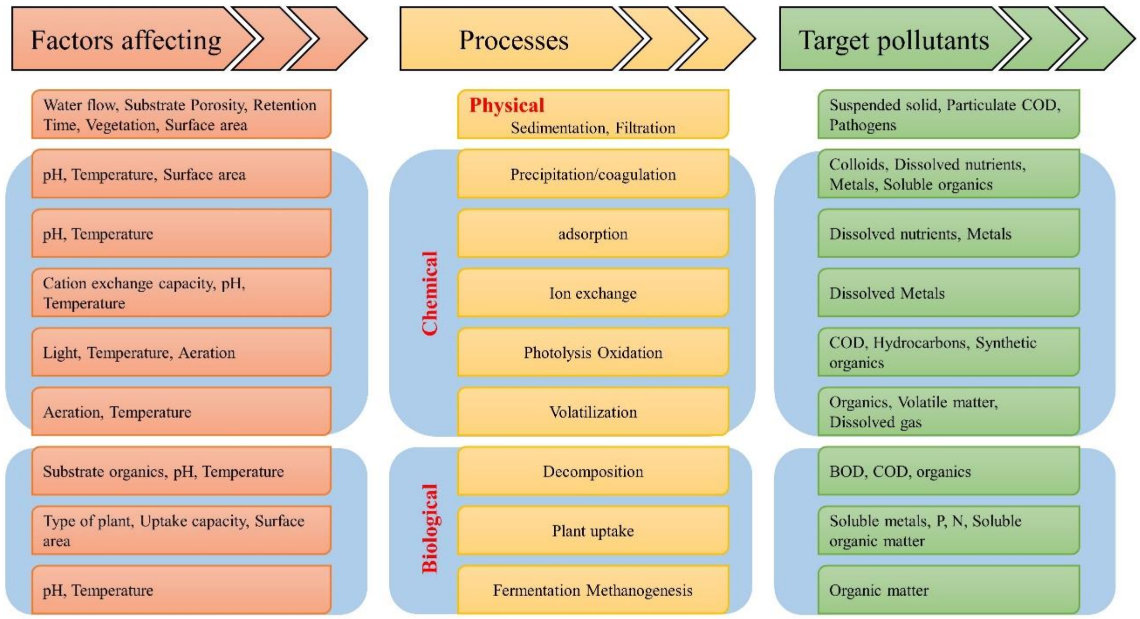

Fig. 3. The mechanism in the CW process to remove contaminants [22].

The pH and temperature of the wastewater were directly measured in each reactor using a pH meter and a portable multiparameter thermometer. To obtain accurate measurements, the wastewater was allowed to reach equilibrium in each reactor for approximately two hours before the measurement. Fluctuations in pH and temperature occurred throughout the study, with a notable decrease in pH and an increase in temperature on the fourth day. This decrease in pH and increase in temperature coincided with a decrease in BOD_5 and COD, indicating a direct correlation. The shifts in pH and temperature might have been influenced by factors such as alkalinity and reduced biodegradation during the wastewater treatment process. However, it is essential to note that the treatment process could still achieve pollutant removal efficiency, even at cold temperatures (<5 °C) [26]. The findings of this study revealed that the average pH value of domestic wastewater in CW1 and the filtration reactor was 6.34, whereas in CW2, it was 6.32. Furthermore, the average temperatures in CW1, CW2, and the filtration reactor were 29.02℃, 28.94℃, and 28.98℃, respectively.

Compared to previous studies, there is a slight difference in pH, with an average of 6.22 and a temperature range of 30.2-30.4℃ [20]. The slightly lower temperature in this study might be attributed to rainwater mixing during the domestic wastewater sampling process, which could affect pH due to the fermentation of organic matter and the presence of turbidity. Nonetheless, the pH of the domestic wastewater in this study conformed to the regulations listed in Table 1. The optimal temperature range for the growth of decomposing microorganisms in wastewater is typically 30-35℃ [27]. When the pH approached acidity and the temperature increased, it accelerated the wastewater degradation process, thereby enhancing pollutant removal efficiency [20].

3.4. BOD removal rate efficiency

CW treatment and filtration techniques are equally effective in removing BOD from domestic wastewater. The effectiveness of these methods was evaluated through a five-day incubation period to determine BOD_5 concentrations, as shown in Figure 6.

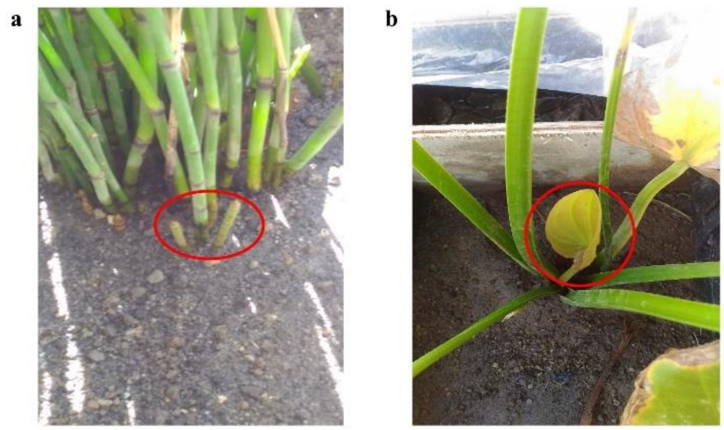

Fig. 4. Growth of new shoots during the acclimatization process of (a) water bamboo and (b) water jasmine.

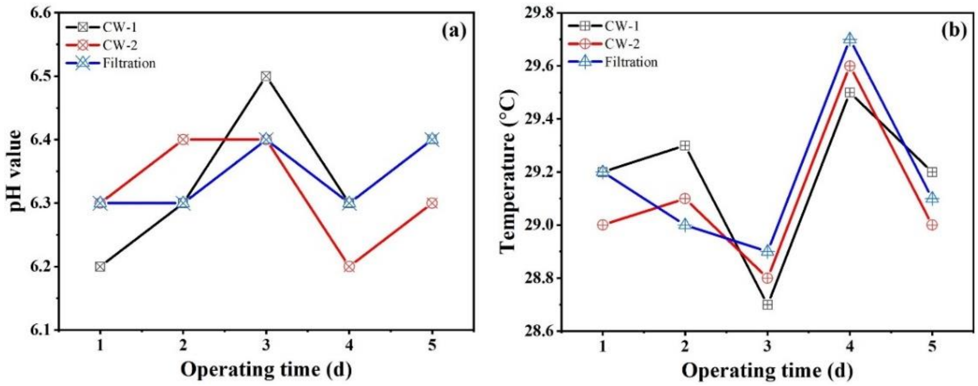

Fig. 5. (a) pH value and (b) temperature in the reactor during study.

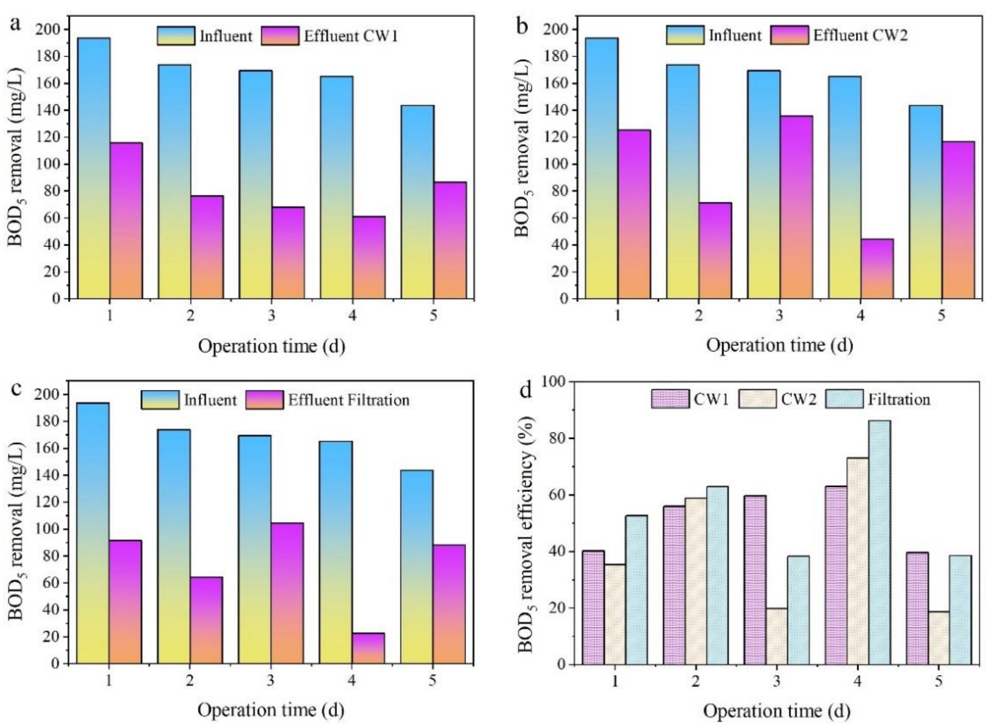

Fig. 6. BOD_5 removal rate: (a) CW1, (b) CW2, (c) filtration, and (d) removal efficiency for all process.

Daily monitoring of influent and effluent wastewater was conducted to assess the efficiency variances between different treatment approaches. The influent values for the urban domestic wastewater treatment ranged from 143.78 mg/L to 193.71 mg//L. A recent study used a new hybrid anaerobic/anoxic digester (HD) system as a pretreatment for vertical subsurface CW (VF) in domestic wastewater treatment. The average BOD_5 concentration for received municipal wastewater (MW) was 101 ± 66 mg L^{-1}, whereas that for Fortified MW was 258 ± 113 mg L^{-1} [6]. After examining the results of the urban domestic wastewater treatment using combined CW and filtration systems, it was evident that there was a consistent decrease in BOD_5 concentration in the influent each day. Overall, the treatment system demonstrated a reduction in BOD_5 concentration. The most significant average decrease for all reactors (CW and filtration) occurred on the fourth day of the treatment. The BOD_5 efficiency values varied, as depicted in Figure 6, particularly in CW2 and filtration. The highest BOD_5 removal concentrations were achieved in CW1 (62.15 mg/L), CW2 (44.43 mg/L), and filtration (22.69 mg/L), with an initial concentration of 165.34 mg/L. BOD_5 removal efficiency varied among the three reactors. In general, all treatment reactors (CW and filtration) showed remarkable results in removing BOD_5 contaminants. Notably, on the fourth day, the filtration reactor exhibited higher BOD removal than CW1 and CW2. The highest efficiency values were observed for CW1 (63.01%), CW2 (73.12%), and filtration (86.27%). The superior efficiency of the CW reactor could be attributed to the involvement of pollutant-absorbing plants and the use of planting media that also functioned as filter media. Conversely, the filtration reactor relied solely on filter media for pollutant removal. However, the results obtained from the filtration reactor slightly outperformed those of the CW reactor. The treated wastewater might contain various pollutants, including small and large particulates, as well as bacteria and viruses, all of which contributed to the increase in BOD.

In a CW reactor, the mechanism for eliminating BOD_5 involves both plant absorption and filtration through growing media. Plants primarily absorb pollutants through their roots, transfer them to the stems and branches, and ultimately evapotranspired through the leaves. On the other hand, the filtration system relies on filter media to remove BOD_5. Media such as sand effectively filters and traps small and large particles. Additionally, coral media serve as a breeding ground for microorganisms that decompose contaminants in domestic wastewater. Variations in BOD_5 values are observed in the CW in domestic wastewater treatment systems, depending on the presence or absence of recirculation. BOD_5 removal without recirculation can reach 90%, which increases to 96% after implementing 50% and 100% recirculation. However, the two methods had no statistically significant difference [28]. Another study found that the application of a CW using natural soil (Oxisol) mixed with sand media and planted with rice plants (Oryza sativa L), as well as a control CW without plants, achieved BOD removal rates ranging from 97% to 99% [29].In a pilot-scale CW system with a hydraulic loading rate of 0.8 m^3/m^2/day, BOD removal was only 76.16% [30]. In a different study, the efficiency of BOD5 removal in slaughterhouse wastewater was 87.37% after treatment with an anaerobic baffled reactor (ABR) treatment system [31].

3.5. COD removal rate efficiency

The CW system demonstrated efficacy in removing COD contaminants from urban domestic wastewater. In some instances, various forms of domestic wastewater treatment are employed to produce clean water for reuse in various applications, offering advantages such as reduced expenses for clean water and other purposes [2]. The data indicated a decrease in influent values from the first to the fifth day of observation. However, the effluent values exhibited more fluctuations, especially in CW2 and the filtration treatment, as shown in Figure 7. Upon careful analysis, the results obtained from the CW were more noteworthy than those from the filtration reactor. Nevertheless, if considering the highest removal efficiency, the filtration method proved to be more effective in removing COD than CW1 and CW2, especially during the treatment conducted on day four.

The average concentration of COD during the observation period was 342.57 mgO_2/L, with the highest recorded at 445.08 mgO_2/L and the lowest at 306.97 mgO_2/L. The elevated COD levels in wastewater can be attributed to the presence of substances that resist oxidation by the reagent used, necessitating the use of $KMnO_4$ for oxidation. The highest maximum efficiency value across all reactors was achieved on the fourth day of the study. The reactors demonstrated significant COD reduction rates, resulting in high efficiency. Specifically, the CW1 reactor successfully removed up to 114.98 mg/L of COD or 66.65%, CW2 removed up to 93.90 mgO_2/L or 70.32%, and the filtration system effectively removed 48.05 mgO_2/L of COD or 84.81% from an initial concentration of 316.40 mgO_2/L.

The collaboration of plants, planting media, and microorganisms within the CW system facilitates COD removal from wastewater. These components work together to eliminate COD from wastewater.

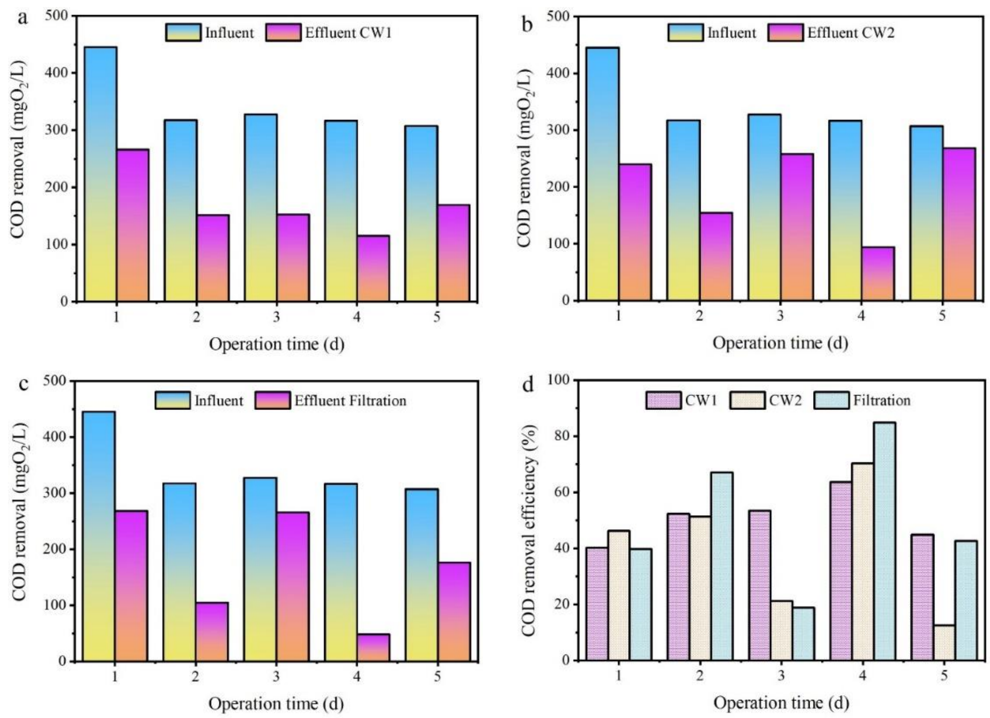

Fig. 7. COD removal rate: (a) CW1, (b) CW2, (c) filtration, and (d) removal efficiency for all process.

Organic substances in wastewater serve as nutrients for plants and support their photosynthetic processes. Moreover, microorganisms attached to sand and coral media play a significant role in reducing COD concentrations. The duration of contact between wastewater, plants, and planting media also affects the effectiveness of the COD reduction. A study reported that a CW achieved a 57.34% reduction in COD in domestic wastewater [30]. However, other studies have shown better results, with an average COD reduction of 80.63% [32]. Horizontal subsurface flow CW systems have demonstrated favorable outcomes for various physicochemical and biological parameters, including COD, across different types of wastewater [33]. The treatment of chicken slaughterhouse wastewater with an ABR system can reach a peak COD removal of 92.69% after being processed for 30 hours [31].

3.6. TSS removal rate efficiency

The trends observed in BOD and COD removal differed from the increase in TSS values observed during the early stages of the study, followed by a decrease towards the end. The high influent TSS value observed throughout the study indicated the presence of abundant organic and inorganic materials in domestic wastewater. These materials typically consist of particles larger than 2 μm in size, including inorganic substances, algae, bacteria, sediment sand, plankton, leaves, grass, and other organic and inorganic substances. Prior to treatment, TSS levels in wastewater usually range from 155 to 330 mg/L, which subsequently decrease following primary and secondary treatment processes [34-35]. The concentration of suspended solids in effluent is influenced by various factors, including plant roots, root decay, dust deposition from the air, and moss growth. These factors contribute to the overall mass of suspended substances and can increase TSS values. In this study, the average influent TSS concentration was 667.80 mg/L, which continued to increase to over 800 mg/L. The influent TSS value in this study fell within the medium category, with a value of approximately 700 mg/L, as shown in Figure 8.

The performance of the CW and filtration systems in removing TSS was exceptional, as shown in Figure 8. Despite the high initial influent values across all reactors, the effluent values remained relatively high, on average. All systems' TSS removal rates exceeded 90%, with CW1 achieving 92.90 mg/L, CW2 reaching 99.70 mg/L, and filtration achieving 90.80 mg/L. The highest removal values were observed on the fourth day of treatment, at 79.5 mg/L in CW1, 108 mg/L in CW2, and 70 mg/L in the filtration reactor, with an initial influent value of 784 mg/L. Notably, there were no significant differences in efficiency values among the three reactors. The highest efficiencies attained by CW1, CW2, and filtration were (89.86%), (86.22%), and (91.07%), respectively. The reduction in TSS occurs through precipitation, aided by the planting media that acts as a filtration medium, effectively trapping both large and small solids within the media [2].

In the context of wastewater treatment using a novel combined hybrid digester in conjunction with a CW system, the efficiency of TSS was 98%, with an average influent concentration of 32 ± 17 mg TSS L^{-1} [6]. Winter and Goetz [36] noted that it is crucial to maintain the effluent concentration for TSS below 100 mg TSS L^{-1} in order to prevent bed clogging. In this study, it is worth noting that the TSS effluent values remained below the threshold from the third day of operation, as mentioned earlier, aligning with the recommendations put forth by Winter and Goetz [36].

Nonetheless, it is essential to acknowledge that these results did not achieve the quality standards outlined in East Java Governor's Regulation No. 52 of 2014. Although the treatment process involving CW and filtration yielded noteworthy removal results for all domestic wastewater pollutant parameters, full compliance with the standard set forth by the East Java Governor's Regulation No. 52 of 2014 was not attained [16]. This can be understood by considering that in this study, CW and filtration were utilized exclusively as pre-treatment stages for domestic wastewater prior to subsequent treatment processes.

5. Conclusions

Pretreatment of urban domestic wastewater using CW and filtration systems demonstrated remarkable efficiency in removing BOD, COD, and TSS. The highest average efficiency for these three wastewater parameters was observed on the fourth day of treatment. When the wastewater pH approached acidity, and the temperature rose, it enhanced the efficiency of removing domestic wastewater pollutants. The inclusion of plants and growing media as filtration components significantly contributed to the removal of BOD_5, COD, and TSS. Among the measured parameters, TSS exhibited the most pronounced reduction compared to BOD_5 and COD. Overall, the filtration system yielded slightly better results than the CW reactor in the treatment of urban domestic wastewater. This could be attributed to the pollutant absorption mechanism in the filtration media, which effectively filtered small and large particles and other contaminants trapped within the media, a task that plants cannot accomplish alone. Despite the impressive removal rates obtained, the treatment results in this research did not meet the quality standards outlined in the East Java Governor's Regulation No. 52 of 2014. Nonetheless, these findings provide valuable insights into applying CW and filtration systems for the biological pretreatment of urban domestic wastewater before further processing.

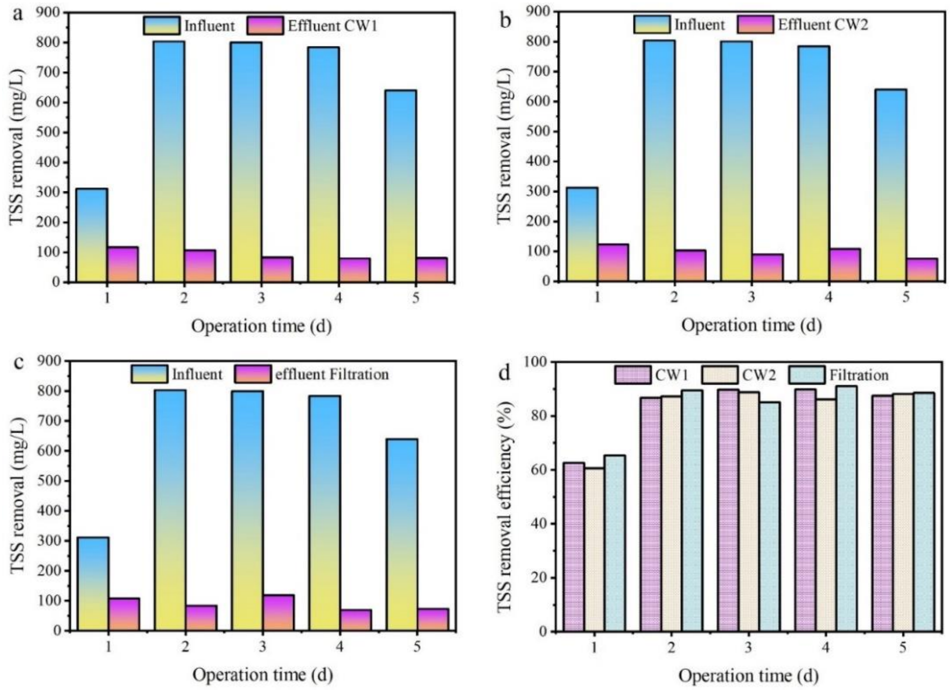

Fig. 8. TSS removal rate: (a) CW1, (b) CW2, (c) filtration, and (d) removal efficiency for all process.

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