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Effectiveness of Combined Gravel and Silica Sand at Varying Contact Filtration Times for Coffee Processing Wastewater Pollutant Removal

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ABSTRAK

Variasi media filtrasi dan waktu tinggal berperan penting dalam optimalisasi perbaikan kualitas air limbah. Tujuan penelitian ini yakni merekomendasikan variasi ketinggian dari kombinasi media filtrasi dari batu kerikil dan pasir silika (SiO_2) serta waktu kontak dalam penanganan metode fisika pada perbaikan kualitas air limbah pengolahan kopi. Terdapat tiga variasi kombinasi ketinggian batu kerikil dan pasir silika yakni 10:5 cm (T1); 7,5:7,5 cm (T2); dan 5:10 cm (T3), dengan dua variasi debit yakni 5,5 mL/detik; dan 9,5 mL/detik. Hasil kajian menunjukkan bahwa variasi ketinggian media batu kerikil dan pasir silika berpengaruh positif terhadap reduksi polutan pada air limbah pengolahan kopi. Semua perlakuan menggunakan tiga kali ulangan untuk mendapatkan data standar deviasi dari penelitian. Rekomendasi terbaik metode fisika untuk penanganan air limbah pengolahan kopi yakni kombinasi ketinggian 5 cm batu kerikil dan 10 cm pasir silika (T3) dengan debit 5,5 mL/detik. Kombinasi perlakuan ini mampu mereduksi parameter kekeruhan, Chemicals Oxygen Demand (BOD), Biochemical Oxygen Demand (COD), ammonia (NH_3), and phosphate (PO_4) secara beurutan sebesar 61,65±1,43%; 49.00±6.66%; 50.66±4.35%; 53,75±4,35%; dan 76,99±4,54%, proses memerlukan hydraulic retention time selama 4 jam. Hasil percobaan ini dapat digunakan sebagai referensi aplikasi variasi ketinggian batu kerikil dan pasir silika (SiO_2) dengan mempertimbangkan hydraulic retention time pada primary treatment penyisihan polutan air limbah agroindustri.

Kata kunci**:** filtrasi, penanganan fisika, pengolahan air limbah kopi, waktu kontak dan tinggal

ABSTRACT

Variations in filtration media and hydraulic retention time are important factors in optimizing wastewater quality improvement. The objective of this study is to recommend the optimal height level of gravel and silica sand (SiO2) combination and contact time in physical treatment methods for improving the quality of coffee processing wastewater. Three height-level variations of the gravel–silica sand filtration media combination were tested, namely 10:5 cm (T1), 7.5:7.5 cm (T2), and 5:10 cm (T3), along with two flow rate variations of 5.5 mL/second and 9.5 mL/second. All treatments were conducted in three replications to determine the standard error of the experimental data. The best-performing treatment was a combination of 5 cm gravel and 10 cm silica sand (T3) at a flow rate of 5.5 mL/second, which reduced turbidity, Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), ammonia (NH_3), and phosphate (PO_4) by 61.65±1.43%, 49.00±6.66%, 50.66±4.35%, 53.75±4.35%, and 76.99±4.54%, respectively, at a hydraulic retention time of 4 hours. The height level of the gravel and silica sand (SiO_2) media, along with the optimum hydraulic retention time, had a positive effect on reducing pollutant content in coffee processing wastewater.

Keywords**:** coffee wastewater processing, filtration, hydraulic retention times (HRT), physical treatment

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1. INTRODUCTION

The development of downstream coffee commodities into green bean is growing quite rapidly in Indonesia. The quantity of green bean coffee exports is quite high in 2021 - 2023, which has an impact on Indonesia being ranked 11th as a coffee exporting country (Fitriani et al., 2021; Rondhi et al., 2024). The increase in coffee exports in Indonesia is 3% per year (Syifahati et al., 2021; Zudhi et al., 2024). The increasing trend of processing coffee fruit with wet or semi-wet processing methods for the production of good quality green beans has the potential to increase wastewater also. The volume of coffee processing wastewater in several coffee processing units averages 30 L/ton (Novita et al., 2023).

Exposure of coffee wastewater to water bodies or land if it is no handled first, cause the phenomenon of decline and even pollution of water and land resources. In line from these cases, coffee processing wastewater has characteristics of a dark brown color, has a distinctive odor, has a low degree of acidity, and contains high of dissolved organic matter (Cruz-Salomon et al., 2018; Ijanu et al., 2020; Campos et al., 2021). Coffee processing wastewater does not meet the wastewater quality standards that refer to the Minister of Environment Regulation No. 5/2014. Some previous studies, the values of Total Suspended Solid (TSS), Biochemicals Oxygen Demand (BOD), and Chemicals Oxygen Demand (COD) are 1700 - 2500 mg/L; 600 - 3670 mg/L; and 1340 - 5500 mg/L, respectively (Lemma and Debebe, 2023). Furthermore, coffee processing wastewater has a fairly high level of turbidity and tends to be brown color. Disruption of the performance of the aquatic ecosystem will be experienced if coffee wastewater is discharged into water bodies in the long term. One important aspect that requires to be considered in wastewater treatment is the selection of handling methods or stages.

The combination method of filtration and adsorption plays an important role as an initial or primary treatment that can maximize the removal of wastewater pollutants at the secondary and tertiary stages (Ong, 2018; Kato and Kansha, 2023). Gravel and silica sand (SiO_2) are some of the most effective media for filtration. Gravel functions as a filter that can hold pollutants that are larger than the gaps between its, thus reducing the buildup of particulates and supporting silica sand to absorb better. Silica sand is quite effective at filtering and adsorbing particles in water and is usually used for initial filtration. In line with these cases, the application of silica sand as a filtration media is able to reduce the content of suspended solids and dissolved organic matter in laundry wastewater and domestic waste i.e. 70 - 80% (Seng et al., 2018; Alftessi et al., 2021). Furthermore, the combination of gravel and silica sand as filter media is expected to retain and absorb pollutants in coffee processing wastewater so that it is expected to meet environmental quality standards. The advantage of using this filter media is that it can be used repeatedly after cleaning.

Several factors affect the effectiveness of filtration media performance, both the use of gravel and silica sand, namely variations in the height of the filter media, contact time or hydraulic retention time (HRT), and the flow method of the filtration process (Ong, 2018). Silica sand with 80% thickness of the biofilter can reduce phosphate content by 70%, while gravel is able to retain suspended solids in domestic wastewater by 30-40% (Kubo et al., 2022; Guerrero-Brontons et al., 2024). The application of gravel and silica sand is still individual and not integrated in wastewater treatment. Optimal wastewater discharge must be considered in supporting filtration effectiveness, to regulate the contact time of coffee processing wastewater with filter media. Furthermore, the longer or optimal the HRT will be the better in reducing the pollutant content in the waste (Rehman et al., 2020; Xia et al., 2023). However, to date, gravel and silica sand have mostly been studied and applied individually rather than as an integrated filtration system, and no prior study has specifically evaluated the combined effect of gravel silica sand media height (composition) and contact times on coffee processing wastewater treatment.

This represents a clear research gap, since coffee processing wastewater's distinct characteristics high organic load, low pH, and high turbidity mean that optimal media height and times contact values established for domestic or others wastewater sources cannot be directly assumed to apply. The novelty of this study lies in evaluating gravel and silica sand as a combined, integrated filtration system with systematically varied media height and contact time specifically for coffee processing wastewater, to identify the combination that yields the highest pollutant removal efficiency. The research objective to recommend variations in the height level of gravel and silica sand (SiO2) and contact times in physical treatment methods in improving the quality of coffee processing wastewater.

2. MATERIAL AND METHODS

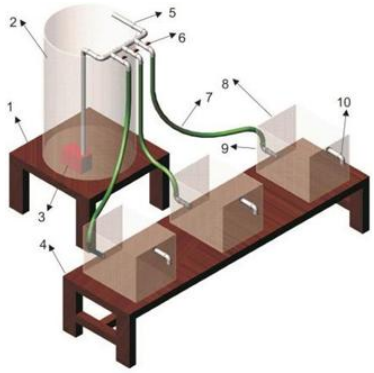
2.1. Material and Tools

The materials used of this research were coffee processing wastewater, silica sand (SiO_2) with a diameter of about 0.5 - 1 mm, and gravel with a diameter of about 10 - 15 mm. Then the materials of samples analysis (pro analysis) were ion-free distilled water, COD High Range (HR) reagent, $MnSO_4$ 40%, alkaline iodide azide, H_2SO_4 20 N, 0.025 N thiosulfate solution, and 5% amylum indicator solution. Furthermore, the equipment used in this study consists of filtration installations and supporting equipment. The filtration installation consisted of a plastic reservoir with a total volume of 50 L, rubber hoses and Polyvinyl Chloride (PVC) pipes with a diameter of 1.8 cm equipped with faucets, and the

glasses aquarium with dimensions of 40 cm × 30 cm × 30 cm or 36 L. Furthermore, stopwatch, iron ruler with dimensions of 50 cm, turbidimeter model TN 100 (Brandmark Thermo Scientific Eutech with accuracy of 1.10-2 NTU), analytical balance (Brandmark Ohous 1.10-4grams), COD reactor model HI 839800 (Brandmark Hanna), spectrophotometer model HI 83099 (Brandmark Hanna), 125 and 250 mL winkler bottles (Brandmark Pyrex), and pHmeter 223 (Brandmark Hanna). Details of the filtration plant design with gravel and silica sand media are presented in Figure 1.

2.2. Experimental Design

The experimental procedure i.e. flowed the coffee processing wastewater simultaneously at the main tap. Up flow is the chosen method of flowing coffee wastewater, because this method is more effectively applied in filtration (Leon-Becerril et al., 2016). Water discharge levels of 5.5 mL/second (small) and 9.5 mL/second (medium) were obtained by adjusting the opening of the faucet. Furthermore, wastewater was flowed simultaneously into T1, T2, and T3 and it were mentioned in Table 1. This experiment was three replications to identify standard error data of treatments. Effluent of coffee processing wastewater was tested on turbidity parameters, Biochemicals Oxygen Demand (BOD), Chemicals Oxygen Demand (COD), Phosphate (PO_4), and Ammonia (NH_3). The picture of the filtration installation circuit equipped with variations of gravel and silica sand media can be seen in Figure 2.



Legend:

1. Reservoir table
2. Plastic reservoir
3. Pump
4. Aquarium table
5. PVC pipes
6. faucets
7. hoses
8. aquarium
9. inlet
10. outlet

Figure 1. Filtration Installation with Gravel and Silica Sand Media

Table 1. Experimental Design

Discharge	Treatments Code in the Aquarium		
	T1	T2	T3
5.5 mL/second (small)	10 cm gravel:5 cm silica sand	7.5 cm gravel:7.5 cm silica sand	5 cm gravel:10 cm silica sand
9.5 mL/second (medium)	10 cm gravel:5 cm silica sand	7.5 cm gravel:7.5 cm silica sand	5 cm gravel:10 cm silica sand

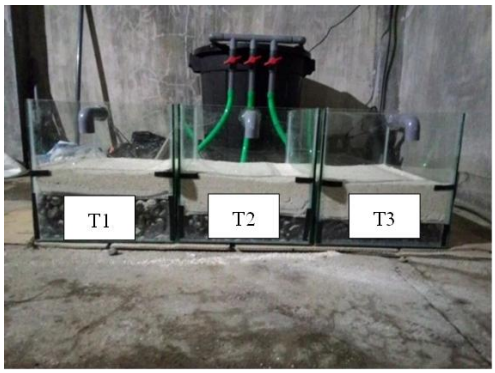


Figure 2. Filtration Installation with Varying Height of Gravel and Silica Sand Media

2.3. Data Analysis

The effectiveness of coffee processing wastewater filtration with factor height level variations in gravel and silica sand media and discharge was evaluated refers to the optimal Hydraulic Retention Time (HRT) and the percentage of pollutant reduction (RP). The equations used to identify HRT and RP can be seen in formulas 1 and 2 (Anggarini et al., 2015; Novita et al., 2023), respectively. Both equations were used to recommend the best alternative from the height level and combinations of gravel and silica sand, as well as coffee wastewater discharge. The recommendation was determined based on the quantitative synthesis analysis of the highest RP value.

$$HRT = \frac{V}{Q} \qquad (1)$$

Where HRT is the residence time in units of hours, V is the working volume of coffee wastewater m^3, then Q is the discharge of coffee wastewater or flow rates with units of m^3/hour.

$$RP = \frac{(C1 - C2)}{C1} \times 100\% \qquad (2)$$

Where RP is the reduction of pollutants in wastewater %, C1 is the initial concentration of coffee wastewater mg/L, and C2 is the end concentration of coffee wastewater mg/L.

3. RESULTS AND DISCUSSION

3.1. Characterization of Coffee Wastewater Processing (CPW)

Coffee processing wastewater showed high concentrations of polluting parameters and exceeds the established quality standards. Details of the initial condition of coffee processing wastewater before handling filtration method with variations in filtration media and discharge can be seen in Table 2. The parameter values in coffee processing wastewater when it will be discharged into water bodies must comply with the quality standards set by Regulation of the Environment Ministry of Republic of Indonesia No. 5 of 2014 concerning wastewater quality standards for businesses and/or activities of the coffee processing industry.

Table 2. Coffee Wastewater Processing Characterization

Parameters	Initial Conditions of Coffee Wastewater Processing	Wastewater Standard*
pH	4.10 - 4.70 ± 0.14	6 - 9
Turbidity (NTU)	594 ± 10	-
BOD (mg/L)	1.757 ± 5	90
COD (mg/L)	2750 ± 6	200
N in Ammonia (NH_3) (mg/L)	132 ± 7	-
Phosphate (PO_4) (mg/L)	29 ± 1	-

**Source: Environment Ministry of the Republic of Indonesia, (2014).*

Referring to the data on Table 2, it can be seen that the pH of coffee processing wastewater ranging from 4.10 - 4.70 ± 0.14 is acidic and has not met the quality standards of 6-9. COD levels reached 2750 ± 6 mg/L which exceeded the predetermined quality standard threshold of 200 mg/L. The same thing happened to the BOD level, which reached 1.757 ± 5 mg/L, which exceeded the 90 mg/L standard threshold. Thus, untreated coffee processing wastewater is not suitable for direct discharge into water bodies or the environment, so it to be treated so that the waste can meet the predetermined quality standards and can be discharged directly into water bodies or the environment.

Wet processing of coffee to reduce the mucilage layer produces excess compounds that have the potential to pollute the environment such as melanoidin, soluble organic matter, and low pH values (Ijanu et al., 2020; Rondhi et al., 2023). In line with this case, several studies mention that wet processing of coffee which includes pulping, fermentation, and washing processes change the complex compounds such as hemicellulose and melanoidin so that the resulting wastewater can be cloudy brown in color, high in organic matter, and increase the value of dissolved solids (Gururaj et al., 2021; Asefaw et al., 2024). As from previous studies, coffee processing wastewater produces COD values exceeding 10,000 mg/L and has a pH below 4, so it is necessary to carry out initial or primary treatment such as filtration and adsorption to reduce these pollutants (Novita et al., 2023; Lemma et al., 2023).

3.2. Effectivness of Filtrations Process

The effectiveness of filtration with gravel and silica sand media was assessed based on the percentage value of pollutant removal. Furthermore, the comparison of the percentage value of pollutant removal refers on the discharge used can be seen in Figure 3 with a discharge of 5.5 mL/second and Figure 4 with a discharge of 9.5 mL/second. Referring to both figures, the filtration treatment of coffee processing wastewater with variations in the height level of gravel and silica sand can reduce turbidity, BOD, COD, phosphate, and ammonia parameters.

In all treatments, there was a decrease in the turbidity parameter. The filtration process is smooth so that it can reduce the turbidity value of coffee processing wastewater. The long or optimum contact time of coffee wastewater with gravel and silica sand so that the opportunity for coffee wastewater to settle, retain and be absorbed by the filter media is increasing. Referring to Figure 4. It is known that the highest turbidity removal value is in the T3 treatment with HRT 4 hours or 5.5 mL/second discharge and PR values is 61.65 ± 1.80% (T3), then the lowest efficiency is in the T1 treatment with HRT 2 hours or discharge 5.5 mL/second and PR value is 57.77 ± 1.33%. These results show that the higher the silica sand, the greater the decrease in turbidity. It is caused by the amount and length of waste passing through the sand media so that many substances that cause turbidity are absorbed in the silica sand media (Fitriani et al., 2023). The utilization of silica sand as a filtration media is able to cover two processes, namely filtration and adsorption, so that the sorption of colloids and other dissolved particles can run optimally (Benhabiles et al., 2022). Furthermore, the effect of HRT variation on pollutant removal with the best filter combination (T3) is presented in Figure 5.

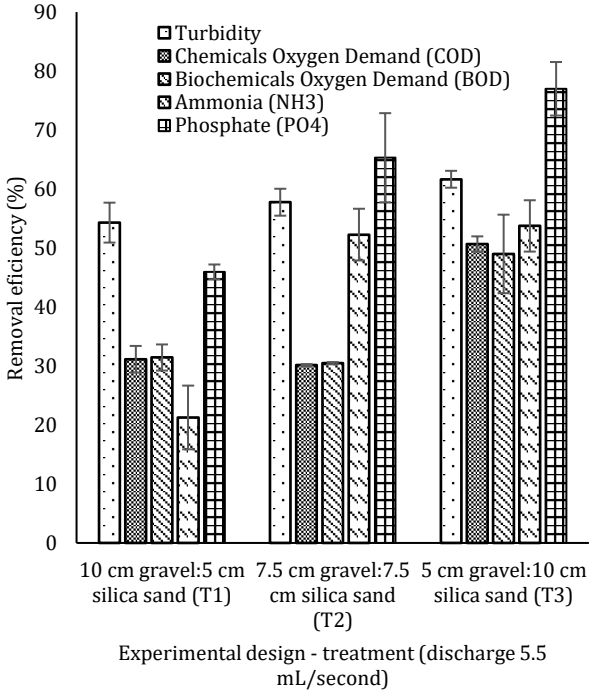


Figure 3. Removal Efficiency with Discharge of 5.5 mL/second

The removal of organic matter as indicated by the BOD and COD values is also successful. In line with this, in Figure 4, all treatments experienced a successful decline in BOD and COD. The decrease in COD and BOD values indicates that the need for dissolved oxygen is decreasing, causing the small amount of organic matter to be decomposed. These conditions provide an opportunity for aerobic microbes to oxidize perfectly (Novita et al., 2023). Furthermore, the PR of BOD and COD of the best treatment T3 is 49.00±6.66% and 50.66±4.35%,

respectively. Referring to Figure 5, the best HRT to reduce dissolved organic matter to reach 50% is a discharge of 5.5 mL/second. Flow with an up-flow system and adequate contact time can reduce BOD and COD optimally. This is in line with the results of filtration with silica sand media with single stage and multistage methods with slow flow of laundry, restaurant, and industrial waste capable of reducing BOD and COD parameters by 25 - 80% (Seidmohammadi et al., 2021; Yahya et al., 2023).

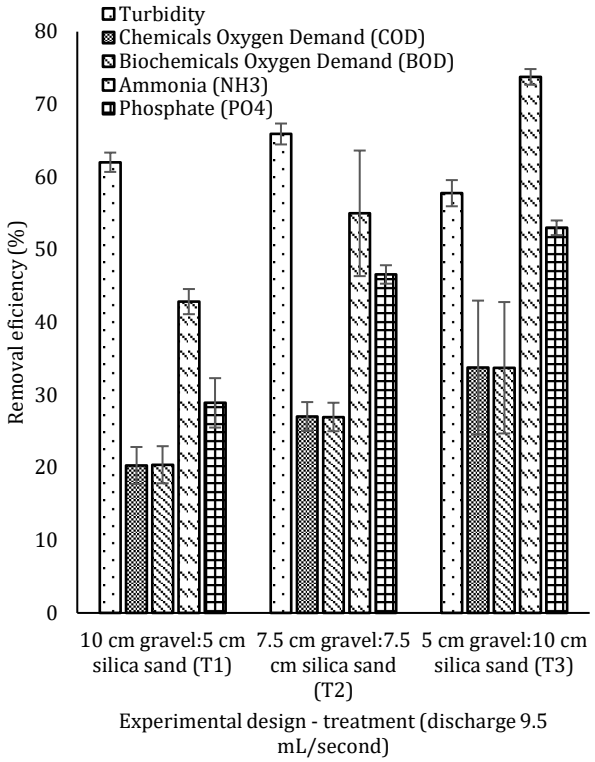


Figure 4. Removal Efficiency with Discharge of 9.5 mL/second

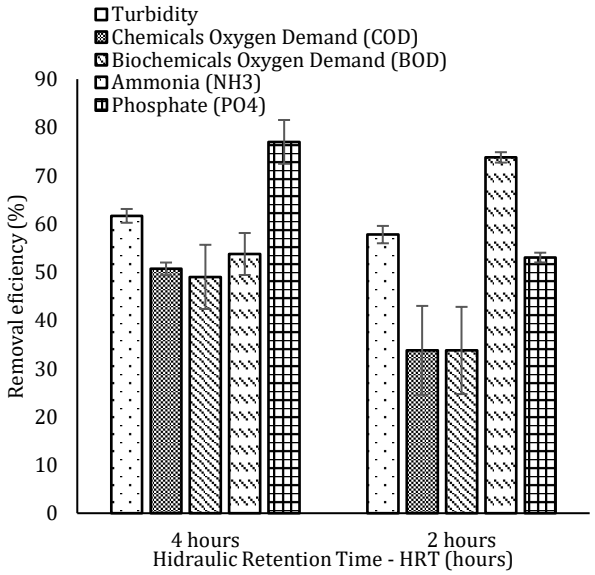


Figure 5. HRT Variation of Pollutant Removal in Coffee Processing Wastewater

Filtration with gravel and silica sand media is also quite effective in reducing phosphate and ammonia content. HRT for 4 hours and a combination of silica sand with a height level of 10 cm (T3) had phosphate and ammonia removal values of 53,75±4,35% and 76,99±4,54%, respectively. The principle of filtration with this up-flow method maximizes the process of filtering colloids and microorganisms and is thought to have an impact on reducing the content of ions such as phosphate and ammonia (Warmadewanthi and Larasati, 2020). Another function of the filtration process is the separation of particles that can be absorbed by gravel and silica sand, then able to reduce the effect of odor on wastewater. This is supported by the results of research related to the handling of laundry and industrial wastewater with the silica sand filtration method with a height of 10 cm, which has an effective reduction in phosphate and ammonia values of 65 - 83% (Sengupta et al., 2015). The effect of filtration with gravel and silica sand media with HRT 2 - 4 hours also has a positive impact in stabilizing the pH value of coffee processing wastewater based on Figure 6.

The effluent filtration of coffee processing wastewater has a pH value that tends to be neutral in the 4-hour HRT treatment, namely 6.34 - 6.65±0.14. The pH value at HRT 2 hours also increased, namely 5.53 - 5.70±0.15. The increase in pH value is caused by the exchange and trapping of H+ ions in the filter media, both gravel and silica sand. Sand is a type of silica and oxygen compound in water in the form of colloids that bind H^+ on the surface to form a positively charged layer and can increase the pH value by 7% (Mazeikiene and Sarko, 2022). In line with the results of this study, the use of sand and gravel as laundry waste filtration media can increase the pH value by 5.8 - 7.1 (Yaseen et al., 2019). Thus, the HRT of 4 hours and a silica sand height level of 10 cm is an adequate alternative filtration method in improving coffee wastewater quality.

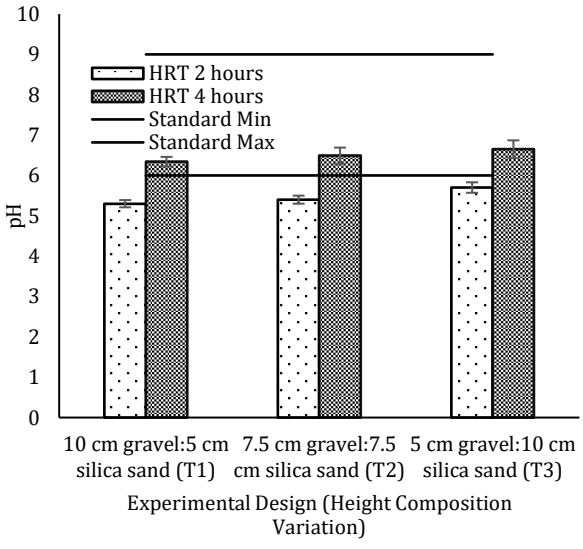


Figure 6. pH Value of Coffee Processing Wastewater

The treatment combines three physical mechanisms. Gravel performs sedimentation and coarse filtration, intercepting suspended particles larger than the gaps between its grains and reducing particulate buildup in the lower media layer. Silica sand then performs fine filtration and adsorption, capturing smaller suspended solids and binding dissolved organic matter. Together, these mechanisms progressively remove pollutants from the coffee processing wastewater as it passes through the filter bed. Then, the scematic diagram of the reasech is shown in Figure 7.

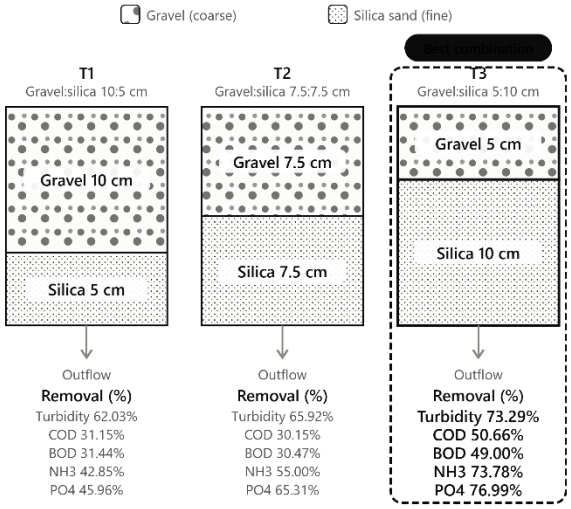


Figure 7. The Schematic Diagram of Research

Recommendations for the use of gravel and silica sand in coffee processing wastewater are in the treatment of 5 cm gravel: 10 cm silica sand, with a discharge of 5.5 mL / second or HRT for 4 hours (T3). The treatment has the highest pollutant removal value including turbidity, BOD, COD, phosphate, and ammonia parameters, and can stabilize the pH value. The application of this filtration method as the primary stage of coffee wastewater treatment can be used as a reference and consideration of the pre-treatment stage even though the COD and BOD parameters do not meet the established quality standards. Furthermore, coffee processing wastewater effluent, which tends to be biodegradable and has a neutral pH, can be handled by bioremediation methods (Novita et al., 2023).

4. CONCLUSION

Filtration of coffee processing wastewater with gravel and silica sand (SiO_2) media has a positive impact on improving the quality of coffee processing wastewater. The best recommendation for filtration of physical methods for handling coffee processing wastewater is T3 with the height level of 5 cm of gravel and 10 cm of silica sand with a discharge of 5.5 mL/second. This treatment combination is able to reduce the parameters of turbidity, Chemicals Oxygen Demand (BOD), Biochemical Oxygen Demand (COD), ammonia (NH_3), and phosphate (PO_4) respectively by 61.65 ± 1.43%; 49.00 ± 6.66%; 50.66 ± 1.31%; 53.75 ± 4.35%; and 76.99 ± 4.54%, the process requires hydraulic retention time for 4 hours. The results of this experiment can be used as a reference in the primary treatment for the application of variations in the height level of gravel and silica sand (SiO_2) by considering the hydraulic retention time in the primary treatment of coffee agroindustry wastewater pollutant removal.

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