

Application of Solar UV Radiation in the Photo-Fenton Process for Coffee Agroindustry Wastewater Treatment

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ABSTRACT

Wastewater from coffee agro-industrial activities tends to be brown in colour and high values of TSS and rich in organic matter is indicated by BOD and COD values, potentially causing environmental pollution. Biological treatment has not been fully effective in reducing its colour due to the presence of dark pigments. This study evaluates the efficiency of sunlight ultraviolet radiation compared to artificial UV lamps in purifying coffee processing wastewater using the photo-Fenton method. The research stages consisted of preparation including photoreactor installation and formulation of Fenton reagent doses of H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$; ultraviolet radiation process; and analysis of the pollution reduction parameters. The results show that the application of ultraviolet radiation from sunlight better than using artificial ultraviolet from lamps on the quality of coffee agroindustry wastewater. The recommended treatment combination of $\text{Fe}_2(\text{SO}_4)_3$ 0.0015M and H_2O_2 0.2M is the best alternative for improving its quality which has reduction efficiency (RE) namely 96.27% (TSS), 97.68% (turbidity), 99.98% (colour absorbance), and 95.17% (COD) respectively. The results of this experiment offer an alternative tertiary treatment for coffee agroindustry or Small and medium enterprises (SMEs) wastewater that is effective, efficient, low-cost, and relatively easy to implement.

Key words: Advanced oxidation processes (AOPs); coffee wastewater processing; photo-Fenton; solar UV.

1 INTRODUCTION

Coffee is one of the fastest-growing agricultural products in the world, with consumption growth of 1-2% per year (Mangku et al., 2022; Poncet et al., 2024). Furthermore, the coffee agroindustry is one of the sectors that plays an important role in supporting the economies of several countries, such as Brazil, Colombia, Vietnam, Kenya and Indonesia (Wanzala; Marwa; Wanga, 2024; Rokhman et al., 2023). Coffee production in Indonesia is forecast to increase between 2022 and 2026. Processing coffee fruit using water, known as wet processing, has the potential to produce wastewater and tends to be less environmentally friendly (Ijanu et al., 2020; Campos et al., 2021; Firdissa et al., 2022). The water input used in processing coffee with this method can reach 7-9 m³ per ton of coffee fruit (Novita et al., 2023).

Wastewater generated from coffee processing tends to be brown in colour and contains high levels of organic matter. The colour mainly comes from dark pigments containing melanoidin. These pigments are dissolved and then oxidised in coffee processing wastewater (Feng et al., 2023; Moya-Ramirez et al., 2023). Melanoidin is the end product of the Maillard reaction, consisting of ligand groups such as tannins and polysaccharides (Langner; Rzeski, 2014). It has macromolecular properties and is dark brown in colour, which

is difficult to degrade by physical or biological treatments (Ijanu et al., 2020). Coffee effluent has a dark colour and contains a significant amount of dark pigment. It which is considered the final product of the Maillard reaction and contributes to a high concentration of COD and others organic matters exposures (Wang et al., 2021). The effluent does not have a high concentration of Biochemicals Oxygen Demand (BOD), hence it is difficult to treat biologically. The dark colour can be dangerous for aquatic life as it blocks rays from the sun; it also creates toxicity in the environment. This highlights the importance of toxic component removal in coffee effluent. The main composition of the such effluent is melanoidin. The dark brown colour derived from melanoidin can block light thus inhibiting the photosynthesis process and endangering aquatic life if discharged directly into water. Based on previous research by Novita et al. (2023), it is known that coffee processing wastewater effluent has a pH ranging from 3.8-5.5; TSS ranging from 127-140 mg/L; COD ranging from 3360-3762 mg/L; and turbidity ranging from 395-523 NTU. The high content of organic matter in wastewater results in a reduced amount of oxygen in the water, which has the potential to cause pollution if discharged directly into water bodies or the environment without prior treatment. Therefore, it is necessary to perform appropriate wastewater treatment to degrade the colour and reduce the organic matter content

so that it complies with the quality standards regulated in the Minister of Environment Regulation No. 5 of 2014 concerning wastewater quality standards, Appendix XXV, for coffee processing industry businesses and/or activities (Minister of Environment of the Republic of Indonesia, 2014).

The complex structure of melanoidin makes the wastewater difficult to degrade biologically. Some coloured waste treatment methods are considered less effective because they can cause new problems. For example, the application of coffee processing wastewater treatment using anaerobic processes is less than optimal for turbidity and colour parameters because it focuses on the degradation of organic matter with the help of microorganisms (Hailemariam; Velmurugan; Selvaraj, 2021). Furthermore, this method produces effluent that smells bad due to the production of methane gas and ammonia. Several previous studies by Ijanu et al. (2020) and Novita et al. (2023), have been conducted to degrade the organic matter content in coffee wastewater. Chemical treatment using coagulation and flocculation methods (bio-coagulant) resulted in a TSS reduction efficiency of 51%, but its application in small industries requires the use of technology, albeit simple (Shah et al., 2023). Handling coffee wastewater using plants or phytoremediation can produce a COD reduction efficiency of 81.10%, but this requires a longer time (Novita et al., 2023). Alternatively, coffee industry wastewater treatment using anaerobic processes can degrade COD by 80-90%, but the resulting effluent is still dark and murky (Novita, 2016). In general, water quality after the use of physical, chemical and biological methods remains murky, so further treatment is needed to obtain clearer processed water. One effective wastewater treatment is to degrade dark-coloured wastewater through a purification stage with the use of toxic chemical compounds, known as the photo-fenton method, which is a development of advanced chemical oxidation processes (AOPs) (Wang et al., 2016; El-Gawad et al., 2024). The Fenton method works by oxidising organic matter in wastewater with a Fenton reagent and UV irradiation to form OH radicals that degrade organic and inorganic matter in wastewater. The main component in the photo-Fenton process is the formation of OH radicals from the decomposition of hydrogen peroxide as an oxidiser, accelerated by Fe^{2+} ions as a catalyst. The use of UV light in the Fenton reaction accelerates and multiplies the OH radicals formed (Gkorgkolia; Fytianos, 2023). Melanoidin consists of several ligand groups, such as tannin, polysaccharides, peptides, and their combinations. It is antioxidative and toxic to many organisms in waste treatment. Melanoidin can bind Fe^{2+} , so the use of photo-Fenton and Fenton reactions could be effective in degrading melanoidin and removing the coffee colour. Solar radiation is one source of UV light that is freely accessible and abundant. Therefore, the utilisation of UV radiation as a natural resource is considered to be effective, cheap and environmentally

friendly. The combination of UV radiation from the sun and $\text{Fe(III)-H}_2\text{O}_2$ reagent is effective in improving wastewater quality to the point when the standard is reached (Lin; Lin, 2021). Furthermore, the use of solar radiation in wastewater treatment is considered more effective, relatively low cost, and able to reduce COD concentrations by 80-90%, making it effective in the purification process (Pandey et al., 2021; Ali et al., 2022; Brillas, 2023). The photo-Fenton reaction causes rapid decolourisation of coffee wastewater due to the loss of aromaticity associated with melanoidin depolymerisation.

The catalyst commonly used in the photo-Fenton method is $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$. Photo-Fenton is a method with the catalyst $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ that is easy to apply and relatively effective in reducing COD in washing and stripping wastewater (Pandey et al., 2021). In experiments to reduce the quality of laundry and textile wastewater using the Photo Fenton method with $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ catalyst was able to reduce organic matter with a value range of 85-90% (Hamed et al., 2024). One of the factors affecting the optimisation of the process is the formation of OH radicals, which depends on the dose of Fenton reagent, the pH of the solution, and the duration of UV irradiation (Lin; Lin, 2021). In their application, $\text{Fe}_2(\text{SO}_4)_3$ and H_2SO_4 catalysts must be balanced, so that the photo-Fenton process runs optimally. So far, there has been no comparison of the effectiveness of the waste treatment process using natural UV from sunlight or solar and artificial UV from lamps. Several industrial, textiles, and agricultural wastewater treatment studies applied several UV lamps and solar sources separately process (Pandey et al., 2021; Ali et al., 2022; Brillas, 2023). The use of solar UV is considered cheaper and more effective on a large scale and can support the efficiency of natural energy-based WWTP in reducing BOD pollutants in the wastewater by up to 70% (Ponce-Robles et al., 2023; Tharasawatpipat et al., 2025). This study aims to development of utilizing ultraviolet light radiation from the sun and comparing its efficiency with ultraviolet light from lamps in purifying coffee processing wastewater. The application of this method is considered to be relatively effective, with low operational costs, and is easy to apply at the stage of purifying coffee processing wastewater, both on a large industrial scale and in small businesses. It can be used as a reference for the development or scale-up of photo-Fenton-based wastewater treatment plants in downstream coffee or other agro-industry businesses that have low or limited capital, located in tropical areas with abundant sun exposure.

2 MATERIAL AND METHODS

2.1 Materials, Tools and Research Location

The materials used were coffee processing wastewater from the stripping process at the Banjarsengon Coffee House

Coffee Agroindustry, Patrang District, Jember Regency – East Java, Indonesia; chemicals (pro analysis), including $\text{Fe}_2(\text{SO}_4)_3$ (s), H_2O_2 30%(q), NaOH (s), and H_2SO_4 0.1 M (q); ion-free distilled water (aqua destilations); and COD high range (HR) reagent, brand Hanna HI 839800 (detection range 200 - 15,000 mg/L). The tools used for the photo-Fenton process included photo reactors based on compound parabolic concentrator technology with dimensions of 150 cm long, 80 cm wide, 15 cm high, and a 60 cm support, equipped with a 1.5 cm diameter hose and a 1.2 m aluminium reflector (Figure 1: Photoreactor with dimensions); a plastic container with a magnetic stirrer; a hotplate and stirrer (model HP 3100, Fisher Scientific); and a 250 mL Pyrex glass beaker. The tools used for measuring the wastewater quality parameters included a 50 mL Pyrex flask, a 250 mL Pyrex glass beaker, 45 μm Whatman filter paper, vacuum filtration equipment, a 50 mL Pyrex funnel, a glass stirrer, a stopwatch, a pH meter (HI 223, Hanna brand), an Ohaus analytical balance, a turbidimeter (TN 100, Thermo Scientific Eutech brand), aluminium cups, porcelain cups, a UV-vis spectrophotometer, a Memmert brand oven, a COD reactor (Hanna HI 83099), and a digital balance. The photo-Fenton process and research sample tests were conducted at the Environmental Conservation Engineering and Control Laboratory, Agricultural Engineering, University of Jember, Indonesia.

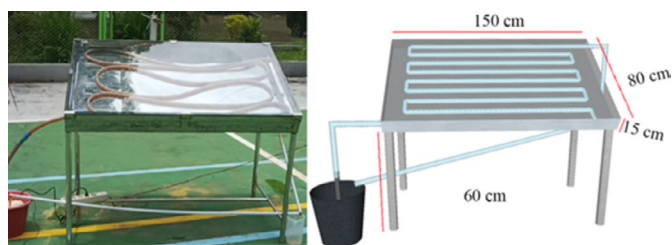


Figure 1: Photoreactor with dimensions

2.2 Preparation of Coffee Processing Wastewater

The filtering stage is conducted to condition the coffee processing wastewater, removing solid substances of significant size, such as coffee fruit skins, mucus clumps, twigs, and similar materials. This step ensures that the photo-Fenton process is not obstructed by these materials, which can impact the formation of OH radicals (Gonzalez et al., 2023). Filtering of coffee processing wastewater is performed using filter with dimensions 40 mesh or 0.475 mm and is accommodated in a 5 L plastic container. The next stage involved measuring the characteristics of coffee processing wastewater, including Total Suspended Solid (TSS), turbidity, colour, Chemicals Oxygen Demand (COD), and pH parameters.

2.3 Determination of Fenton Reagent Dosage and Photo-Fenton Experimental Design

The purpose of determining the reagent dose was to establish the molar range of Fenton reagent doses to be used. The amount of H_2O_2 requirement was based on the initial concentration of COD levels in the wastewater. Theoretical requirements indicate that 2.12 mg of H_2O_2 is needed to oxidise 1 mg of BOD/COD (Gonzalez et al., 2023). Equations (1): hydrogen peroxide concentrations, Equations (2): molarity of hydrogen peroxide and Equations (3) volume of hydrogen peroxides were used to determine the dose (molarity) of H_2O_2 . The need for $\text{Fe}_2(\text{SO}_4)_3$ reagent is determined after establishing the required amount of H_2O_2 , with the amount of $\text{Fe}_2(\text{SO}_4)_3$ catalyst needed being 1/20 to 1/50 of the weight of the H_2O_2 (Nawaz et al., 2022). Additionally, a study by Gonzalez et al., (2023), found that the combination of H_2O_2 0.2 M and $\text{Fe}_2(\text{SO}_4)_3$ 0.0015 M was the best alternative for reducing TSS, turbidity, colour and COD parameters in coffee processing wastewater using the photo-Fenton method with artificial UV. The artificial UV with UV C types lamps has irradiation energy approximately 1,235 lux. These results were used as a reference for determining the dosage of H_2O_2 0.2 M and $\text{Fe}_2(\text{SO}_4)_3$, as they indicated a percentage reduction in wastewater concentration of 72-98%.

$$C_{\text{H}_2\text{O}_2} = \text{COD value} \times 2.12 \quad (1)$$

$$\text{Molarity}_{\text{H}_2\text{O}_2} = C_{\text{H}_2\text{O}_2} \times \text{mr}_{\text{H}_2\text{O}_2} \quad (2)$$

$$V_{\text{H}_2\text{O}_2} = M_1 \times V_1 = M_2 \times V_2 \quad (3)$$

where CH_2O_2 = concentration of hydrogen peroxide (mg/L); $\text{mr}_{\text{H}_2\text{O}_2}$ = relative atomic mass of hydrogen peroxide; M_1 = molarity 1 (M) CH_2O_2 ; M_2 = molarity 2 (M) CH_2O_2 ; V_1 = volume 1 CH_2O_2 ; and V_2 = volume 2 CH_2O_2

After determining the dosage of reagents or catalysts, the process of analysing the characteristics of coffee processing wastewater continued, including TSS, colour, COD and pH parameters. Determining the initial value of COD aimed to establish the amount of H_2O_2 to be used. 5 litres of coffee processing wastewater were placed into a plastic bucket, and the pH of the sample was adjusted to pH 3 using H_2SO_4 0.1 M or NaOH 0.1 M. The optimum pH setting influences the Fenton photo process and prevents the precipitation of iron ions (Nawaz et al., 2022).

The research was organised with a completely randomised design (CRD) involving two factors, H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$, and was repeated three times. The first factor was

the dose treatment of H_2O_2 , which consisted of three treatment levels, while the second factor was the dose treatment of $\text{Fe}_2(\text{SO}_4)_3$, consisting of six treatment levels. The aim was to determine the best combination of Fenton reagent doses (H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$) that would be effective in degrading the organic matter content and colour in coffee wastewater. The experimental design used in the study is shown in Table 1 concerning experimental design. The dosages of $\text{Fe}_2(\text{SO}_4)_3$ was 2.09 g (F1), 4.17 g (F2), 8.34 g (F3), and 16.68 g (F4), while those of H_2O_2 were 56.18 mL (H1), 112.36 mL (H2), and 168.54 mL (H3).

Coffee processing wastewater was mixed with Fenton's reagent at the concentrations shown in Table 1 and homogenised by stirring. The solution mixture was then circulated and exposed to sunlight in the photoreactor for 60 minutes, followed by precipitation for 60 minutes in the sun. This process was conducted between 10:00 am and 2:00 pm West Indonesia Time (Waktu Indonesia Barat or WIB), when the weather was sunny and not cloudy. It is estimated the number of irradiation energy approximately 6,610 – 120,000 lux (Indonesia Region of Tropical Area), then the energy is considered effective to support photo-Fenton process in the quality of wastewater treatment (Das: Adak, 2022, Zakaria et al., 2023). The optimum UV irradiation time was 60-90 minutes (Mansour et al., 2019). The filtrate obtained was analysed for characteristics including TSS, colour, COD and pH parameters. TSS analysis was conducted gravimetrically (SNI 6989.3:2019); that of COD analysis by using a closed reflux spectrophotometer (SNI 6989.2:2019);

colour absorbance was analysed spectrophotometrically (SNI 6989.80:2011); and pH analysis was made using a pH meter (SNI 6989.11:2019). The observation data were then used to calculate the efficiency value and analysed using statistical methods. The statistical methods use analysis of variance (Anova) two ways with error level values ($p < 0,05$ or 5%). The number of samples were 36 treatments, then all treatments impact results were tested by Anova methods to identify final parameter values i.e. TSS, COD, colour absorbance, and turbidity.

3. RESULTS

3.1 Initial Conditions of Coffee Agroindustry Wastewater

The sample used was coffee wastewater after undergoing the stripping process. Its initial characteristics are presented in Table 2 regarding initial conditions of coffee cherry wastewater processing. Based on these values, the parameters of chemical oxygen demand (COD), total suspended solids (TSS), and pH do not meet the quality standards set by the Minister of Environment Number 5 of 2014. The wastewater used was the output of the pulping process. Coffee processing wastewater in wet processing is mostly generated from the pulping and washing process after fermentation. The results of coffee processing are discharged into a channel near the processing area without any prior treatment. The level of the TSS value obtained in the initial

Table 1: Experimental design.

H_2O_2 (0.1 M)		H_2O_2 dosages		
		H_2O_2 (0.2 M)	H_2O_2 (0.3 M)	
$\text{Fe}_2(\text{SO}_4)_3$ dosages	F1 (0.0015 M)	F1H1 (0.0015 M $\text{Fe}_2(\text{SO}_4)_3$; 0.1 M H_2O_2)	F1H2 (0.0015 M $\text{Fe}_2(\text{SO}_4)_3$; 0.2 M H_2O_2)	F1H3 (0.0015 M $\text{Fe}_2(\text{SO}_4)_3$; 0.3 M H_2O_2)
	F2 (0.0030 M)	F2H1 (0.0030 M $\text{Fe}_2(\text{SO}_4)_3$; 0.1 M H_2O_2)	F2H2 (0.0030 M $\text{Fe}_2(\text{SO}_4)_3$; 0.2 M H_2O_2)	F2H3 (0.0030 M $\text{Fe}_2(\text{SO}_4)_3$; 0.3 M H_2O_2)
	F3 (0.0060 M)	F3H1 (0.0060 M $\text{Fe}_2(\text{SO}_4)_3$; 0.1 M H_2O_2)	F3H2 (0.0060 M $\text{Fe}_2(\text{SO}_4)_3$; 0.2 M H_2O_2)	F3H3 (0.0060 M $\text{Fe}_2(\text{SO}_4)_3$; 0.3 M H_2O_2)
	F4 (0.0120 M)	F4H1 (0.0120 M $\text{Fe}_2(\text{SO}_4)_3$; 0.1 M H_2O_2)	F4H2 (0.0120 M $\text{Fe}_2(\text{SO}_4)_3$; 0.2 M H_2O_2)	F4H3 (0.0120 M $\text{Fe}_2(\text{SO}_4)_3$; 0.3 M H_2O_2)

Table 2: Initial conditions of coffee cherry wastewater processing.

Parameter	Raw wastewater	Wastewater quality standard*	Unit
TSS	394	150	mg/L
Turbidity	332	-	NTU
Colour absorbance	1.43	-	AU
COD	4,000	-	mg/L
pH	4.2	6-9	-

*Source: Regulation of the Minister of Environment of the Republic of Indonesia Number 5 of 2014 Concerning Wastewater Quality Standards.

characteristic measurement, 394 mg/L, was above the established quality standards. Water turbidity was 332 NTU. The high value was caused by the large number of suspended particles, such as rinds and mucus remnants, resulting from the pulping and washing stage. The brown-coloured coffee processing wastewater can be seen in Figure 2 regarding image of raw coffee cherry wastewater.



Figure 2: Image of raw coffee cherry wastewater

The initial colour absorbance value of the coffee processing wastewater was 1.43 AU, so visually it appeared brown, as shown in Figure 2 regarding image of raw coffee cherry wastewater. Melanoidin is formed from reducing sugars and proteins or amino acids. The COD value in the coffee wastewater of 4,000 mg/L exceeded the established quality standards. The pH value of coffee wastewater is classified as acidic, at around 4.2. This low value is caused by the remnants of mucus contained in the coffee skin (Dadi et al., 2018; Montes et al., 2023).

3.2 Reduction Efficiency and Recommendation

Variations in the addition of H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$ had a positive impact on reducing pollutants and purifying coffee processing wastewater refer to Figure 3 regarding percentage of reduction efficiency (RE). The treatments significantly affected the turbidity and COD parameters. Among these, H2F1 (H_2O_2 0.2 M and $\text{Fe}_2(\text{SO}_4)_3$ 0.0015 M) emerged as the most effective and efficient, as indicated by the efficiency values shown in Table 3 regarding the comparison of reduction efficiency values of improving the quality of coffee processing wastewater using photo-Fenton with UV-lamps (artificial sources) and UV-solar (natural sources). These

findings align with the results from photo-Fenton treatments using artificial UV light from lamps.

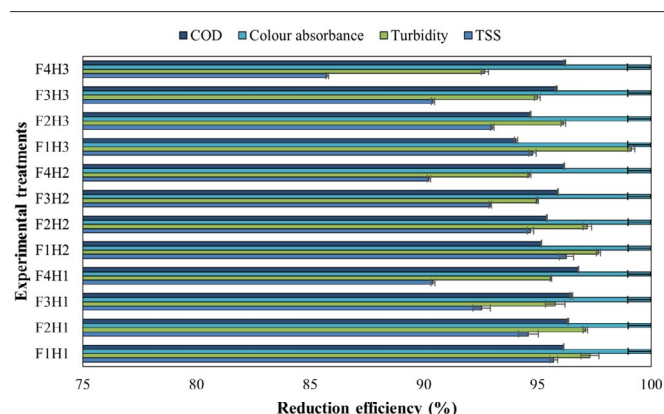


Figure 3: Percentage of reduction efficiency

The equilibrium of the addition of H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$ affected the results of the treatment of coffee processing wastewater, including its visual appearance, pH, and Fe residue content. Insufficient Fenton reagent limits OH radical formation, impairing the photo-Fenton process. Conversely, excessive FeSO_4 increases Fe residue and turns the wastewater reddish. For instance, treatment H2F1 yielded a Fe residue of 45.8 mg/L, exceeding the quality standard of 10 mg/L set by the Minister of Environment Regulation Number 5 of 2014. Additionally, the pH values of processed wastewater ranged from 1.68 to 2.33, indicating acidity. It is showed in the Figure 4 regarding the comparison of pH end values (experimental treatments) with range pH standard.

The photo-Fenton method generally results in acidic effluents, necessitating further treatments such as neutralisation or aeration. Integrating photo-Fenton with adsorption can effectively reduce pollutants and achieve a near-neutral pH (Ijanu et al., 2020; Barros et al., 2020). Therefore, photo-Fenton is recommended as a tertiary treatment for coffee processing wastewater, followed by neutralisation after initial high organic matter removal.

As indicated in Table 3 regarding the comparison of reduction efficiency values of improving the quality of coffee processing wastewater using photo-Fenton with UV-lamps (artificial sources) and UV-solar (natural sources), solar radiation offers greater efficiency than UV lamps for photo-

Table 3: The comparison of reduction efficiency values of improving the quality of coffee processing wastewater using photo-Fenton with UV-lamps (artificial sources) and UV-solar (natural sources).

UV radiation sources	Treatments – Codes	Reduction efficiency (%)			
		TSS	Turbidity	Colour absorbance	COD
UV-artificial*	F1H2 (H_2O_2 0,2 M and $\text{Fe}_2(\text{SO}_4)_3$ 0,0015M) *	95.55*	98.40 *	93.97*	72.47*
UV-solar	H2F1 (H_2O_2 0,2 M and $\text{Fe}_2(\text{SO}_4)_3$ 0,0015M)	96.27	97.68	99.98	95.17

Fenton processes. It is more effective and cost-efficient, providing optimal results for wastewater purification due to its higher energy range (3 to 124 eV) compared to artificial UV light (Velegraki; Mantzavinos, 2015). Future studies should compare the effectiveness of artificial UV and solar UV in photo-Fenton processes for coffee processing wastewater.

4 DISCUSSION

4.1 TSS Parameter Removal

As shown in Figure 3 regarding the percentage of reduction efficiency and Figure 4 concerning comparison of TSS end values end values (experimental treatments) with TSS standard, all the fenton reagent dose treatments combined with UV sunlight irradiation was can reduce the TSS levels of coffee processing wastewater to one meeting the quality standards set by the Minister of Environment Regulation No. 5 of 2014. This is supported by the effluent values being within the range of 13 to 51 mg/L, thus also meeting established quality standards. The TSS content in coffee wastewater comes from the remains of mucus from the previous process (Novita et al., 2023). The TSS reduction efficiency graph in the Figure 3 shows that the highest TSS efficiency value is in the F1H2 treatment combination, at a concentration of H_2O_2 0.2 M and $\text{Fe}_2(\text{SO}_4)_3$ 0.0015 M, achieving 96.27% efficiency and a final TSS value of 13 mg/L. Conversely, the lowest TSS parameter reduction was found in the F4H3 treatment, at a concentration of H_2O_2 0.2 M and $\text{Fe}_2(\text{SO}_4)_3$ 0.0120 M, achieving 85.75% efficiency. The TSS efficiency value increased with the higher H_2O_2 concentration, but with higher of $\text{Fe}_2(\text{SO}_4)_3$ concentration, TSS efficiency tended to decrease. Excessive its can result in the precipitation of phosphate by iron, making the wastewater more turbid due to the phosphate precipitation process. TSS is related to turbidity because suspended solids cause water turbidity; they are not dissolved and cannot settle immediately, and consist of particles smaller in size and weight than the sediment (Barros et al., 2020; Bidira et al., 2022).

The treatment combination of H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$ had a significant effect on reducing the TSS parameters. This was supported by the results of the two-way Anova test and Duncan's multiple range test, which showed that the F value exceeded the F table value. Therefore, there was an effect of the combination of H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$ treatment on the TSS value of coffee processing wastewater. This was inversely proportional to the results obtained for each dose of H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$ because they produced values that were significantly different from each other. The greater the concentration of H_2O_2 , the greater the number of OH radicals formed to oxidise the organic matter content in the wastewater. In treatment H1, the concentration of H_2O_2 added was sufficient to meet the needs for OH radicals to oxidise suspended particles.

4.2 Turbidity Parameter Removal

The Fenton photo process utilising UV from sunlight was effective in purifying coffee processing wastewater, as indicated by the decrease in turbidity values across all treatments. Referring to Figure 3 regarding the percentage of reduction efficiency and Figure 4 concerning turbidity value, this process significantly improved the brightness level of the wastewater, with final turbidity values ranging from 2.39 to 19.95 NTU. The highest turbidity reduction efficiency was achieved with the F1H3 treatment combination, using H_2O_2 0.3 M and $\text{Fe}_2(\text{SO}_4)_3$ 0.0015 M, resulting in 99.12% efficiency. This was followed by the F1H2 treatment (H_2O_2 0.2 M and $\text{Fe}_2(\text{SO}_4)_3$ 0.0015 M), which achieved 97.68% efficiency, while the lowest efficiency was observed in the F4H3 treatment with H_2O_2 0.3 M and $\text{Fe}_2(\text{SO}_4)_3$ 0.0120 M, at 92.68%.

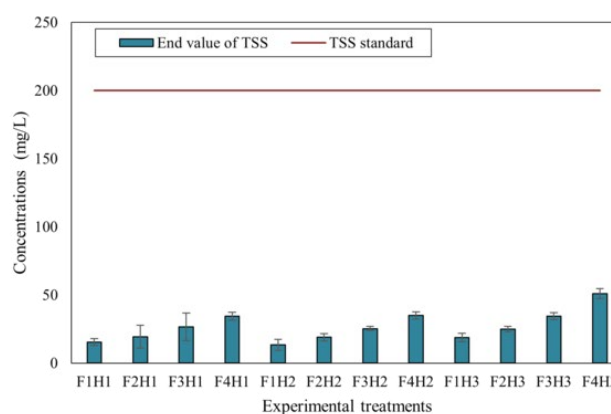


Figure 4 Comparison of TSS end values (experimental treatments) with TSS standard

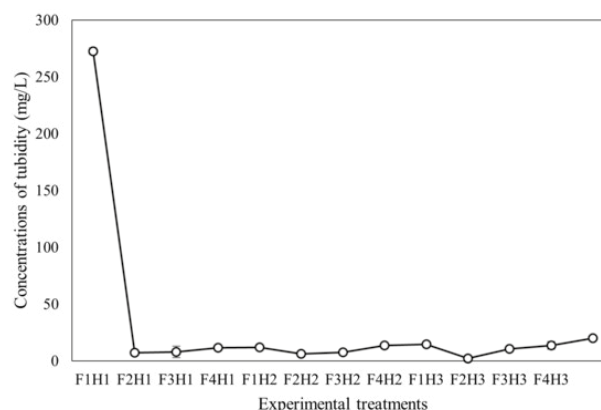


Figure 5: Turbidity value

The decrease in turbidity was attributed to the addition of the Fenton reagent, which oxidises organic matter in wastewater into simpler particles that settle more easily. Fe^{2+} and Fe^{3+} ions act as coagulants, binding suspended solids to form flocculants that settle to the bottom of the solution. However, flocculants that do

not fully precipitate may float and drift, leading to the Tyndall effect, where light is scattered by suspended and dissolved particles, thus reducing efficiency (Ijanu et al., 2024). The treatment combination of H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$ had a significant effect on reducing turbidity parameters. This was supported by the two-way Anova test and Duncan's multiple range test, which showed that the F count exceeded the F table value, indicating that variation of catalysts has a significantly different effect for final turbidity parameters. Therefore, the combination of H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$ had an effect on the turbidity value of coffee processing wastewater. Turbidity values is directly proportional to TSS values, so the reduction in suspended particles was influenced by the number of flocs formed. More flocs lead to a greater reduction in suspended solids in wastewater.

4.3 Colour Absorbance Parameter Removal

The higher the efficiency achieved, the lower the absorbance value produced. A lower colour absorbance value indicates a greater difference from the initial colour of the coffee processing wastewater, as shown in Figure 3 regarding the percentage of reduction efficiency. The high colour absorbance value was caused by the presence of melanoidin. This is a compound formed from the Maillard reaction, which involves the content of coffee pulp, namely sugar, protein, minerals and amino acids (Campos et al., 2021). The wastewater colour becomes clearer with treatment. As shown in Figure 6, all treatment combinations of Fenton reagent doses were able to reduce the absorbance value of the brown coffee wastewater to clear or transparent. The highest turbidity efficiency was achieved with the F1H2 treatment combination, using H_2O_2 0.2 M and $\text{Fe}_2(\text{SO}_4)_3$ 0.0015 M, which resulted in 99.98% efficiency, while the lowest efficiency was observed in the F4H3 treatment with H_2O_2 0.3 M and $\text{Fe}_2(\text{SO}_4)_3$ 0.0120 M, at 99.96%. The decrease in the absorbance value was attributed to the formation of OH radicals, which oxidise organic matter in wastewater into particles that are more easily decomposed. Phenol, a compound that forms melanoidin, is effectively broken down in this process. A visualisation of the coffee processing wastewater purification results using the photo-Fenton process can be seen in Figure 8 regarding visualisation of the colour absorbance of coffee wastewater effluent using UV solar radiation.

The treatment combination of H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$ significantly affected the reduction in colour absorbance in the coffee processing wastewater. This was supported by the results of the two-way Anova test and Duncan's multiple range test, which showed that the F count was greater than the F table, indicating that H_1 was accepted and H_0 rejected. Therefore, the H_2O_2 and $\text{Fe}_2(\text{SO}_4)_3$ treatment combination affected the colour absorbance value. However, the experimental results indicate that increasing $\text{Fe}_2(\text{SO}_4)_3$ concentration results in a reddish colour in the coffee wastewater. This colour change

is due to an excess of iron ions dissolved in the wastewater, which increases the colour absorbance value. Excess FeSO_4 catalyst leads to an abundance of Fe^{2+} ions, which react with the OH radicals, thereby reducing the formation of OH radicals available for colour degradation (Alito; Rantalainen, 2022).

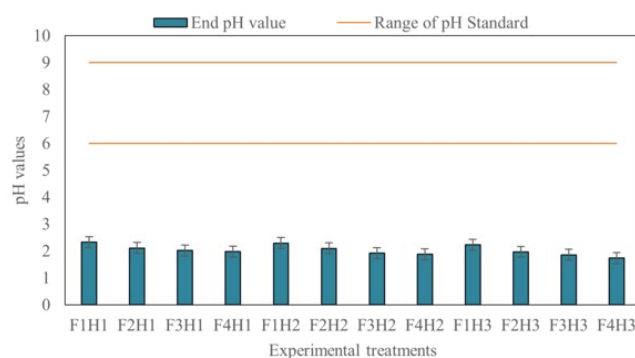


Figure 6: Comparison of COD end values (experimental treatments) with COD standard.

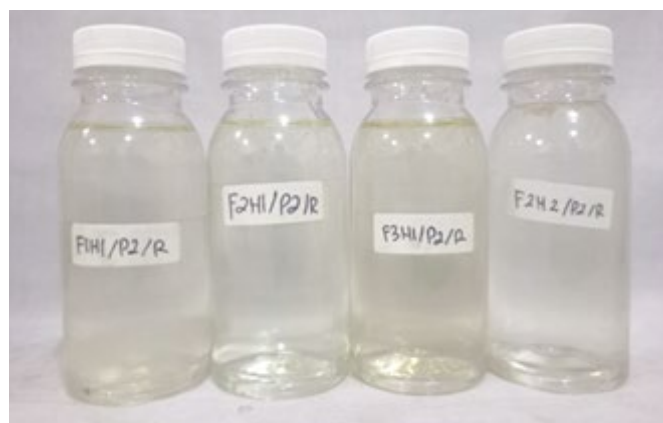


Figure 7: Comparison of pH end values (experimental treatments) with range pH standard.

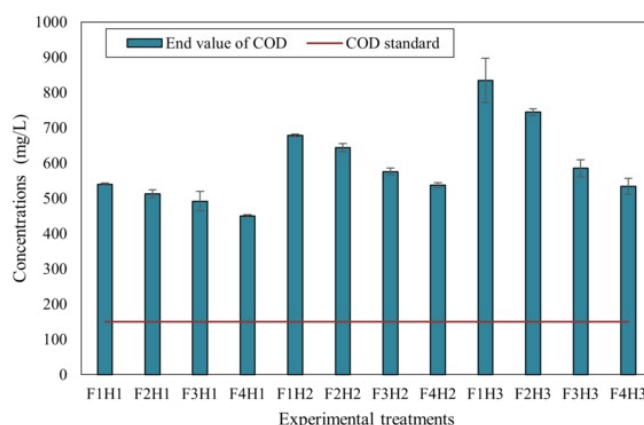


Figure 8: Visualisation of the colour absorbance of coffee wastewater effluent using UV solar radiation.

4.4 COD Parameter Removal

Based on the study results, the highest COD efficiency was achieved with the H4F1 treatment combination, using H_2O_2 at 0.120 M and $\text{Fe}_2(\text{SO}_4)_3$ at 0.0015 M, which resulted in a 96.79% reduction. Conversely, the lowest efficiency was observed in the F1H3 treatment with H_2O_2 at 0.3 M and $\text{Fe}_2(\text{SO}_4)_3$ at 0.0015 M, which achieved a 94.06% reduction (Figure 6). The reduction in COD was attributed to the OH radicals formed during the photo-Fenton reaction [20]. The F1H2 treatment had a COD efficiency of 95.17%, indicating that increased reactions between H_2O_2 and FeSO_4 generated more OH radicals for oxidising organic substances, thus improving efficiency (Gomez et al., 2023). Efficiency decreases when reagent concentrations are unbalanced.

Coffee processing wastewater, with high levels of dissolved organic matter, necessitates the use of H_2SO_4 and FeSO_4 catalysts in the photo-Fenton process as an effective tertiary treatment method. Without prior treatment, the wastewater fails to meet Indonesia's quality standard of 200 mg/L COD. Figure 6 regarding the comparison of COD end values (experimental treatments) with COD standard, shows that all the treatments fell short, with COD values ranging from 450 to 744 mg/L. Excessive or unbalanced reagent addition may increase these values, as exhausted oxidisable compounds and remaining Fenton reagents may be misinterpreted as pollutants. Additionally, unused H_2O_2 residues can react with $\text{K}_2\text{Cr}_2\text{O}_7$, contributing to higher COD readings (Ijanu et al., 2020; Novita et al., 2023).

The combination of H_2O_2 and FeSO_4 significantly affected COD reduction. This was confirmed by the two-way nova and Duncan tests, which indicated that the F count > F table. In the F1H3 treatment, the imbalance in reagent doses resulted in the highest average COD value. Excess H_2O_2 with insufficient Fe^{2+} leads to reduced OH production, while high H_2O_2 concentration or inadequate $\text{Fe}_2(\text{SO}_4)_3$ results in the formation of less reactive hydroperoxyl radicals due to the decomposition of H_2O_2 reacting back with itself (Nawaz et al., 2022). Then, The high value was caused by the presence of chemical compounds such as melanoidin, which is a macromolecular compound that is difficult to degrade biologically or physically (Novita, 2016; Ijanu et al., 2020). This results in a reduced amount of oxygen in the water and increases COD levels if the discharge is made directly into water bodies without prior treatment.

5 CONCLUSIONS

The results show that the application of ultraviolet radiation from sunlight better than using artificial ultraviolet from lamps on the quality of coffee agroindustry wastewater. The recommended treatment combination of $\text{Fe}_2(\text{SO}_4)_3$ 0.0015M and H_2O_2 0.2M is the best alternative for improving its quality

which has reduction efficiency (RE) namely 96.27% (TSS), 97.68% (turbidity), 99.98% (colour absorbance), and 95.17% (COD) respectively. This method is an effective, efficient and relatively easy alternative for tertiary treatment of coffee processing wastewater (small or large scaled).

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7 AUTHOR CONTRIBUTIONS

Conceptualisation Idea: Novita, E.; Methodology design: Novita, E.; Putra, S.R.K.; Pradana, H.A.; Sudirman, N.S.; Data collections: Putra, S.R.K.; Sudirman, N.S.; Data analysis and interpretations: Afriliana, A.; Purnomo, B.H.; Hartono, T.T.; Writing and editing: Novita, E.; Pradana, H.A.; Harsono, S.S.

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