



Coffee waste utilization as an eco–friendly disposal for pollutants removal from wastewater

Mohamed Abdallah, Mohamed Mohsen, Yousef Khaled and Yousef Saad

Supervisor: Mona A. Naghmash, Assistant Professor, Physical Chemistry

Ain Shams University, Faculty of Education, Program General Chemistry

Abstract

The discharge of wastewater containing synthetic dyes from industries, particularly the textile sector, poses significant environmental and health challenges. Waste coffee grounds were examined in this work as a low–cost, environmentally friendly, and sustainable reducing agent for the removal of dyes from aqueous solutions. Coffee waste was collected and pretreated before using. Two methods were used for treating simple treatment and ultrasonic treatment. The waste coffee samples were characterized using X–ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR). The sample catalytic activities were evaluated by reduction of Methylene blue (MB) and Remazol red (RR) dyes. According to the results, waste coffee showed excellent removal efficiency for both MB and RR dyes. The catalytic activity of waste coffee materials is improved by ultrasonic treatment. Ultrasonic treatment improves catalytic activity through raising active site dispersion, decreasing particle size, and improving surface characteristics. The potential of using spent coffee as a sustainable dye remediation method in wastewater treatment systems is highlighted by this study.

Key Words:

Wastewater, dyes, Coffee waste, reduction, Ultrasonic

1. Introduction:

Water is one of the important resources that human beings rely on for

survival and development (Keskin et al., 2021, 102172). The issue of water environment contamination is getting worse because of industry's quick development. Currently, one

of the most pressing issues that every nation in the globe is dealing with is water contamination and the treatment of large concentrations of refractories. Wastewater treatment has become a significant challenge, especially as a result of the growth of pharmaceutical, chemical, dye, and other industries. Moreover, the extreme toxicity of pollutants in water, which primarily consist of aromatic chemicals like nitrobenzene and aniline (Zheng et al., 2006, 277). These compounds contribute to the threat of marine life in all of its manifestations, including vegetation, living things, and direct on humans, either directly through drinking water or indirectly through its use in different food industries, in addition to the fact that it contains human cancer-causing substances (Sarioglu and Atay, 2006, 113–120) (Ehrampoush et al., 2011, 52–59).

One of these pollutants that are studied is the dyes, where there are many dyes, including organic and inorganic. As the dyes of organic origin their concentration increase in wastewater, and about 30% of the dyes cause pollution and formed as a by-product of the dyes used in industrial processes, including the dyes industry, rubber or paper, textile industries, cosmetics, leather industries and other industries as well as pharmaceuticals (Ozer and Dursun, 2007, 262–269). Approximately 20,000 tons of textile dyes from inadequate dyeing are released into the environment each year without any treatment, which can lead to the development of certain diseases (Chequer et al., 2013, 151–176). These risks of dyes on the

people and the environment include the possibility of damage to the kidneys, liver, central nervous system, and human blood, these dyes such as rhodamine B (RhB), methylene blue (MB), methylene orange (MO), and their derivatives (Shao et al., 2020, 143895). The printing and dyeing industries make extensive use of Methylene Blue (MB), which is a popular cationic dye (Mahdavi et al., 2024, 139175). Pure Methylene Blue has medicinal and disinfecting properties, but because of its persistence and possible negative effects on the environment, its presence in wastewater is problematic (Iuliano et al., 2024, 104582). MB dye disturbs aquatic life in aquatic ecosystems by lowering light penetration and photosynthesis. Furthermore, exposure to MB can cause serious health problems, such as skin sensitivity, respiratory problems, and eye irritation (Naeem et al., 2017, 803–811). Reactive dyes like vinyl sulfone dyes are effective on wool, silk, and cotton. Vinyl sulfone dyes are also known as Remazol dyes. Remazol Red (RB-133) is one of these dye examples (El Boraie et al., 2022, 110714). Remazol Red dye (RR) is a big dye that binds to cellulosic fibre with great affinity. Vinyl sulfone dyes are less reactive than dyes manufactured of other materials, therefore the majority of them are either left in the bath dyeing process or are released as industrial effluents (Abo El Naga et al., 2018, 363–373).

The dye pollution problem urged many scientists to search for natural materials that have the ability to remove

pollutants with high efficiency and low costs. Meanwhile, the processes of removing pollutants, whether the traditional chemical or physical methods and biological methods, such as the use of ion exchange processes, membranous separation, adsorption, and many other methods require time and effort in addition to the high costs in their use (Fu and Wang, 2011, 407–418). The goal of wastewater degradation has been met by chemical methods, which primarily involve a sequence of chemical reactions, such as adding chemical reagents, applying light, electricity, microwave, and other techniques to alter the structure or properties of pollutants can be broadly separated into two categories: chemical oxidation and chemical reduction methods. (Zhang and Chen, 2020, 012080). Effectively decontaminating wastewater containing dyes requires the development of cost-effective and ecologically friendly treatment methods. Numerous techniques, including adsorption, ion exchange, extraction, and catalytic reduction, have been documented for the removal of these dyes. The use of the catalytic reduction approach to restore harmful chemicals to the environment has received a lot of attention recently (Din et al., 2024, 100002).

Utilizing hydrogen as clean energy in chemical reactions involving the reduction of unsaturated organic compounds is a crucial technique in current chemistry for the remediation of organic pollutants. In-situ hydrogen synthesis under natural reaction circumstances is a safe technology that could

help address future energy and environmental issues (Benhadria et al., 2022, 249). Investigating several techniques for concurrently treating contaminated water and eliminating impurities is crucial (Miyah et al., 2024, 142236). Hydrogen is a cleaner and more eco-friendly energy source that might be an ideal substitute to fossil fuels (Liu et al., 2013, 147–152). Chemical hydrides have garnered a lot of interest lately as potential long-term fuel sources for on-demand fuel cells. Because of its high hydrogen storage capacity, which is determined by its hydration coefficient, sodium borohydride (NaBH_4) is one of the most preferred chemical hydrides (Chergui et al., 2025, 130094). Nevertheless, hydrolysis is still the only technique used in real-world hydrogen production systems. In this procedure, catalysts are used to convert NaBH_4 into H_2 gas. The characteristics of the catalyst utilized have a major impact on the hydrolysis reaction's efficiency (Chergui et al., 2025, 130094). The conversion of borohydride molecules into hydrogen depends heavily on catalysts, and current research aims to create catalysts that combine high catalytic activity with affordability and environmental friendliness (Zhang et al., 2024, 104820). Because of its ease of use, speed, and high conversion rates, the catalytic reduction of azo dyes using NaBH_4 as the reducing agent has garnered a lot of attention in the field of environmental remediation today (Khalil et al., 2021, 11299–11313). Equation (1) illustrates how sodium

borohydride is hydrolyzed to produce hydrogen (Benhadria et al., 2022, 249).



Coffee husks, coffee silver skin, and coffee grounds are among the waste products produced during the processing of coffee beans (Anastopoulos et al., 2017, 555–565). Half a ton of coffee husks are produced for every ton of coffee that is prepared approximately 6 million tons of coffee grounds are produced annually worldwide (Castillo et al., 2021, 100070). Certain organic compounds found in these wastes, including tannins, caffeine, and chlorogenic acid, can pollute the environment if they are not properly treated (Settera et al., 2020, 112731). Coffee waste must therefore be recycled in order to preserve the environment and possibly increase its energy efficiency, large quantities of lipids, cellulose, and hemicellulose are found in coffee waste polyphenols, proteins, carbohydrates, and a host of other ingredients that can be processed to create useful goods like carotenoids, dietary fiber, biochar, biofuels, flavors, and bioactive compounds (Hoseini et al., 2021, 106009). Coffee waste can be used as an adsorbent in wastewater treatment since recent research has shown that it has good adsorption performance for the removal of both organic and inorganic pollutants in wastewater. It has been reported that raw coffee waste and pretreated coffee waste are widely used as adsorbents to remove pollutants such as heavy metals and dyes.

Many researches have been utilized the coffee waste on the removal of various pollutants (heavy metals, dyes, antibiotics, pesticides, fluorides, and phenols) in wastewater. In addition, the pretreatment method of coffee waste was discussed to solve the problem of limited adsorption efficiency of the original coffee waste (Kang et al., 2022, 103178).

2. The Theoretical Framework

Dye wastewater is increasingly one of the major causes of serious pollution troubles. The primary cause is fast fashion, as rising demand for textiles leads to a corresponding rise in manufacturing, which is correlated with the usage of synthetic dyes (BLINOVÁ and SIROTIK, 2019, 145). Most of these contaminants are known to be toxic and to be harmful to human and animal health, and when they are present in drinking water in excess of a specific threshold, they can be extremely harmful. In order to survive, we require uncontaminated water. This is the primary reason why it is so crucial for people that contaminants be removed from water (Sajid et al., 2018, 400–431).

In order to improve water quality, it is very desirable to design simple, inexpensive, and highly effective materials that can remove pollutants from wastewater. Coffee husk has been used as a starting material for adsorbents to remove both organic and inorganic contaminants in a number of investigations. However, there is a lack of extensive studies on the adsorbents made from coffee waste, including testing them

with actual industrial effluents and examining their regeneration and reusability (Quyen et al., 2021, 131312). Following collection, the coffee waste needs to undergo basic processing, such as washing and drying. Washing is done to get rid of contaminants that could interfere with the adsorption process for wastewater treatment (Oliveira et al., 2008, 1073–1081). The following are some advantages of coffee waste: (i) porous or different cavity structures; (ii) cellulose, hemicellulose, and lignin structures that have a lot of functional groups (such C=O, –COO–, –COOH, and –OH) (Anastopoulos et al., 2017, 555–565) (Dai et al., 2019, 163–172).

The utilization of industrial and agricultural waste products, such coffee waste, to enhance wastewater treatment procedures has gained popularity in recent years. Coffee husk is activated using H_3PO_4 as an adsorbent to remove methylene blue (MB) (Ayalew and Aragaw, 2020, 205–222). Activation raises the specific surface area, which expands the number of adsorption sites available. As the adsorbent dose and contact time increase, the MB removal rate likewise rises. Furthermore, adsorption was more successful in acidic environments. A coffee husk hydrothermal carbon magnetic composite has been produced and employed as an adsorbent for removing MB (Murthy et al., 2020, 205–212). MB was removed using coffee husk. The activated carbon that was carbonized at 108 °C and then treated with KOH was found to have a high MB adsorption capacity (Tran et al., 2020, 138325). Research was done on the potential

of used coffee ground powder (CGP) as adsorbents to remove Rhodamine B/Rhodamine 6G (Rh B and Rh 6G) (Shen and Gondal, 2017, S120–S127). Rh B dye was removed using the pyrrole polymerization process to create the CGW/PPy composite material using potassium persulfate as the oxidant and coffee grounds as the raw material (Ovando–Medina et al., 2018, 171–181). The efficacy of untreated coffee grounds (SCG) to adsorb Malachite green (MG) dye was evaluated (Mat et al., 2018, 012015). Additionally, concentrated sulfuric acid-activated coffee husk (ACH) was tested for removal of MG (Murthy et al., 2019, 192–201). Spent Coffee Ground (SCG) was investigated as a low-cost material for the removal of Congo red (CR) dye (Taufik et al., 2021, 012089). Potassium acetate was used in order enhanced the activity of coffee waste for CR dye removal (Lafi et al., 2019, 160–181). Furthermore, the removal of Crystal violet (CV) dye from wastewater was performed using coffee husks (Cheruiyot et al., 2019, 00116) and untreated Spent Coffee Ground (Loulidi et al., 2020, 569–584).

The majority of organic dyes have harmful and cancer-causing properties. They are also stable for both photodegradation and biodegradation, which will impact aquatic species ability to photosynthesis, endanger aquatic life, and impact human health development (Kang et al., 2022, 103178). This is also true for Orange G, methyl orange (MO), and aniline yellow (AYD). Consequently, these contaminants need to be eliminated before to being released into the

water (Kang et al., 2022, 103178). Consequently, Aniline yellow dye (AYD) and orange G (OG) were eliminated by KOH-activated SCG (Jr. et al., 2020, 111953) (Laksaci et al., 2019, 908–913). In another investigation, coffee waste (CW) was modified using cetyl trimethyl ammonium bromide (CTAB) or cetyl pyridine chloride (CPC) cationic surfactants to improve its affinity for methyl orange anionic dyes (Lafi and Hafiane, 2016, 424–433).

As a result of growing global awareness about wastewater pollution, our project is increasingly focused on sustainable solutions to address this vital environmental concern. One interesting technique is to use wasted coffee to remediate wastewater. Given the substantial amounts of coffee waste generated each year, especially in nations that produce coffee and areas with high coffee consumption, this byproduct offers an intriguing chance to address wastewater contamination. Hence, we concentrated on eliminating two fundamental dyes, Methylene Blue (MB) and Remazol Red (RR), which were selected as models. Here, we employed the reduction approach to remove dyes from wastewater using NaBH_4 .

3. Methods of Research and the tools used

3.1. Materials:

Coffee waste (CW) collected from house, Methylene Blue dye (MB), Remazol Red RB-133 (RR), Sodium borohydride (NaBH_4) and distilled water.

3.2. Tools:

Graduated cylinders, Pipettes, tubes, beakers, measuring flask, balance, funnel, conical furnace and UP50H sonication probe (30 kHz, 50 W).

3.3. Characterization:

X-ray analysis is used to analyse the nature of the solid phase. BRUKER D2 PHASER 2nd gen instrument was used to obtain X-ray diffraction (XRD) patterns. $\text{CuK}\alpha$ radiation at 30KV and 10mA is used. Step sizes of 0.02° and 0.2 seconds per step were used to collect data within the 2θ range of $5-80^\circ$.

The FT-IR Bruker Vector 22 spectrophotometer (cm^{-1}) was used to determine the infrared transmission spectra of different solids, and KBr disks were used to record Fourier transform infrared spectroscopy (FTIR). Between 400 and 4000 cm^{-1} , the infrared spectra was measured. Infrared (IR) spectroscopy is a strong analytical technique used extensively in chemistry and materials science to determine a compound's functional groups.

UV-vis spectroscopy (Jasco V-550 spectrometer) is used to measure reduction activity.

3.4. Treatment of waste coffee sample:

After the coffee waste is collected, simple pretreatment is required, including washing and drying. The purpose of washing is to remove impurities. After collecting the waste coffee was washed and rinsed with distilled water until the brown water turned clear. Then filtered to collect the powder. After that, waste coffee was dried at 80°C for

24 h in the oven. The treated sample was labelled as WC. Another sample was prepared by treatment using ultrasonic. After washing the sample several times, the water solution of coffee waste was sonicated using UP50H sonication probe (30 kHz, 50 W) at room temperature using sonication power 80

% for 30 min. The sample after sonication was filtrated and dried at 80°C for 24 hours the sonicated sample was donated as SWC. Fig. 1 shows the scheme of treatment of coffee waste sample.

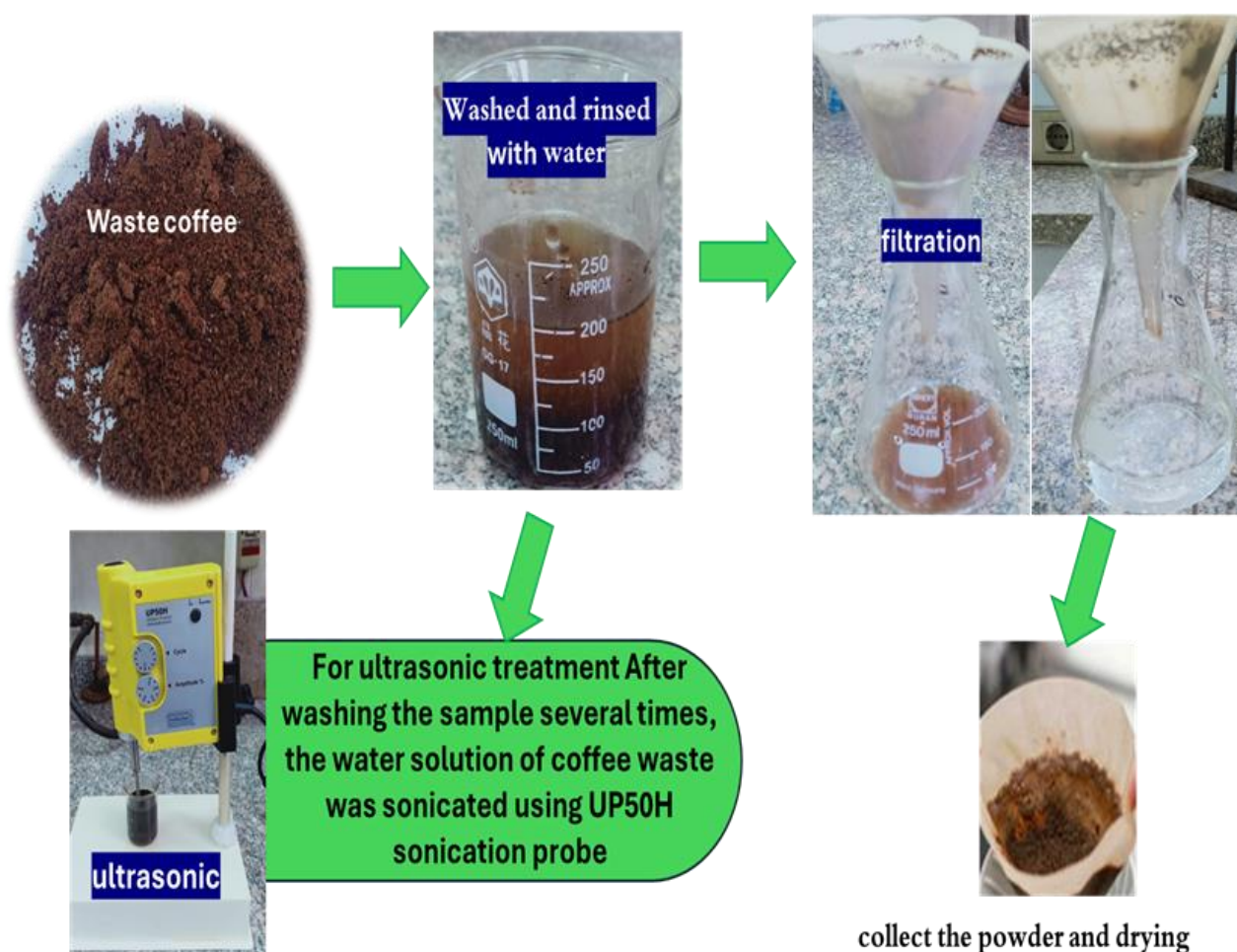


Figure 1: Scheme of treatment of coffee waste sample.

3.5. Catalytic dye reduction:

The performances of the treated waste coffee samples were established for reduction of selected organic dyes. The dyes Methylene blue (MB) and Remazol red (RR) were chosen as the target degrading pollutants,

and NaBH_4 was employed as a reducing agent. For the reduction of dyes, the NaBH_4 (0.01g) was added to 6 ml dye solution ($5 \times 10^{-5} \text{ M}$) in quartz cell, 0.01 g of the coffee sample was then added to the mixture. The concentrations of dyes at various time

intervals are ascertained using the UV–vis absorption spectra. The reduction reaction of dyes is accompanied by the decrease in the absorption peaks at 520 and 664 for RR and MB, respectively.

4. Results of Research

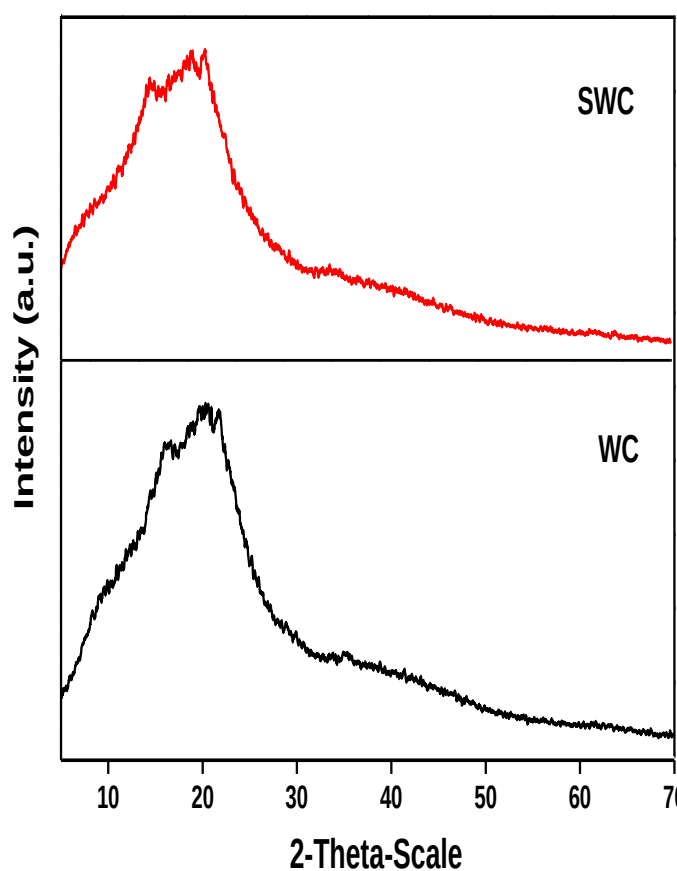


Figure 2: XRD of WC and SWC

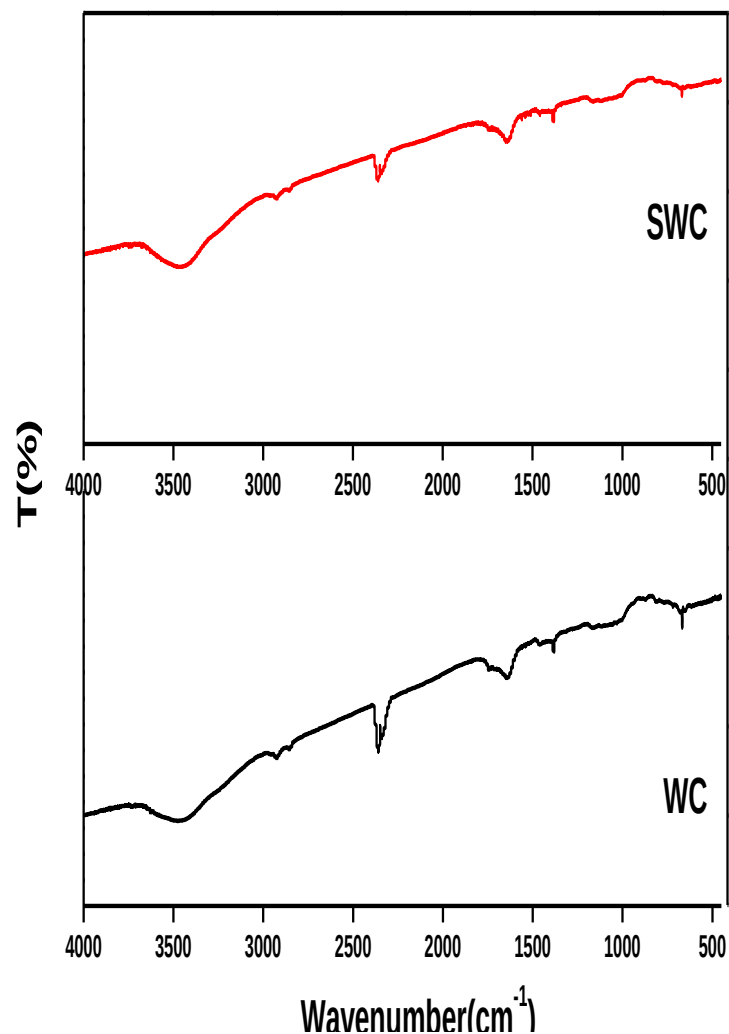


Figure 3: FTIR of WC and SWC

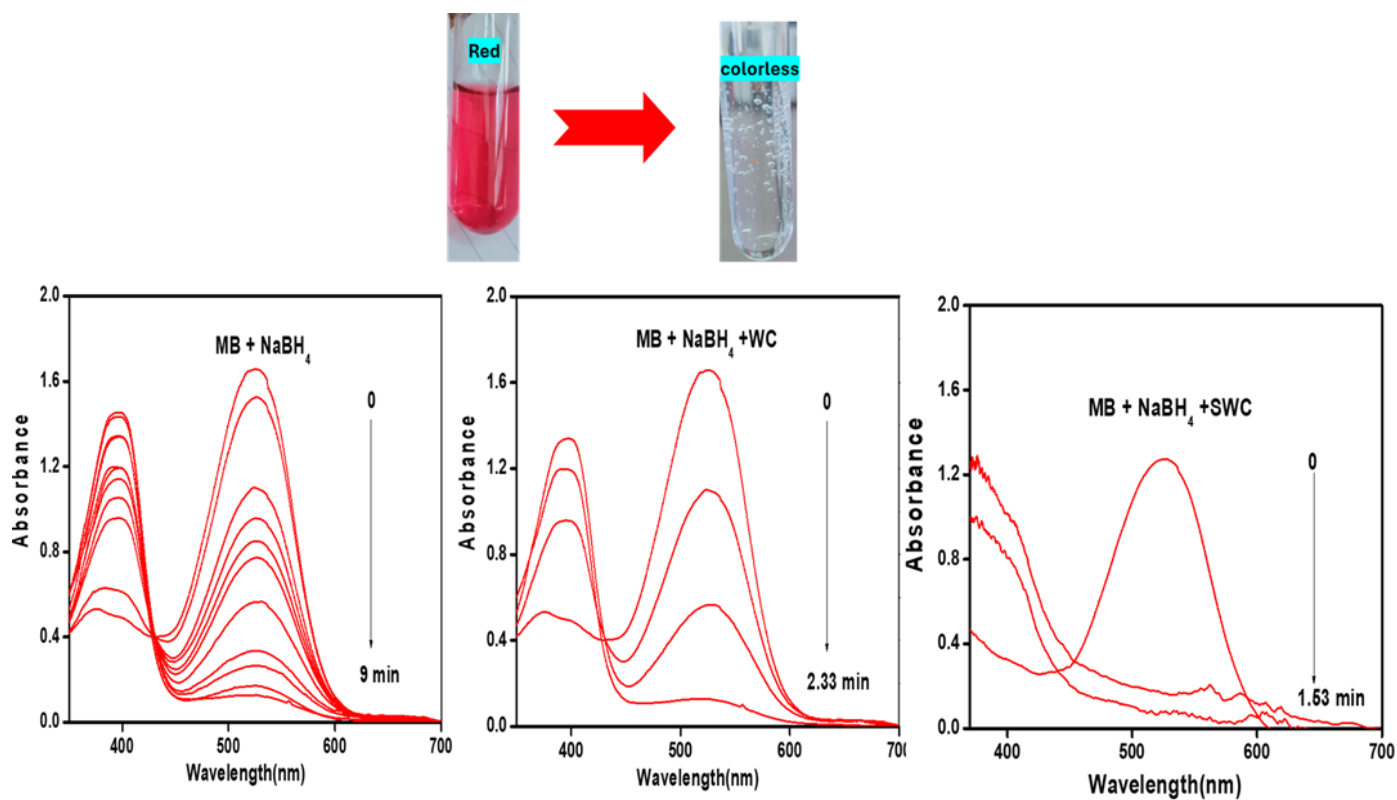


Figure4: UV-vis spectra of RR dye using NaBH_4 only and NaBH_4 with catalyst (WC & SWC)

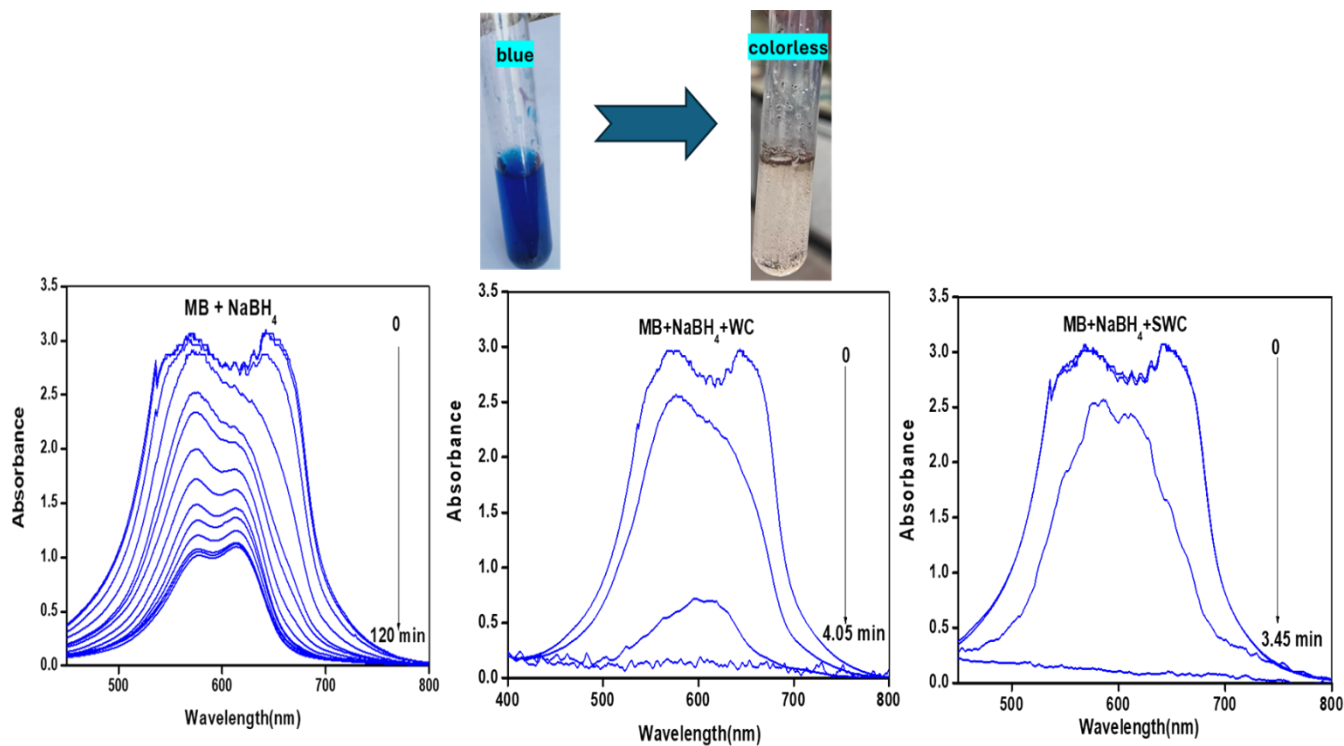


Figure 5: UV-vis spectra of MB dye using NaBH_4 only and NaBH_4 with catalyst (WC & SWC)

Table 1: The reduction time, rate constant (K) and reduction efficiency for the reduction of RR and MB dyes using WC and SWC samples:

Catalyst	Reduction time/min	K (rate constant) min ⁻¹	Reduction efficiency %
<u>Remazol Red (RR)</u>			
WC	2.33	1.03	92.23
SWC	1.53	2.06	95.57
<u>Methylene blue (MB)</u>			
WC	4.05	0.522	87.22
SWC	3.45	0.860	94.17

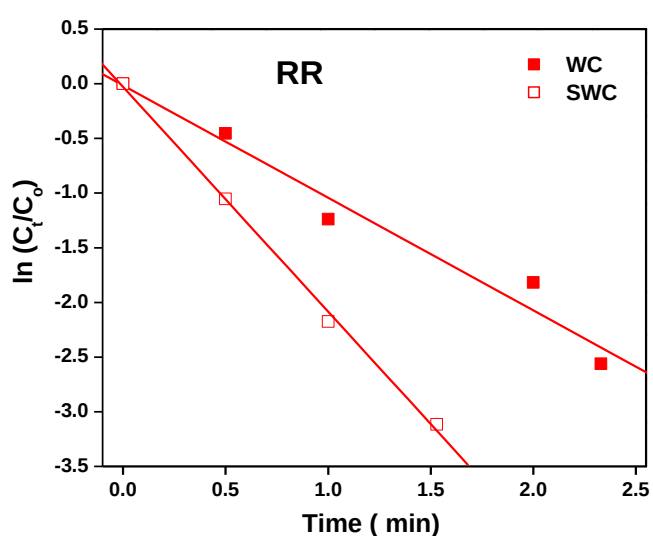


Figure 6: Plots of $\ln C_t/C_0$ versus reaction time (min) for the RR dye reduction

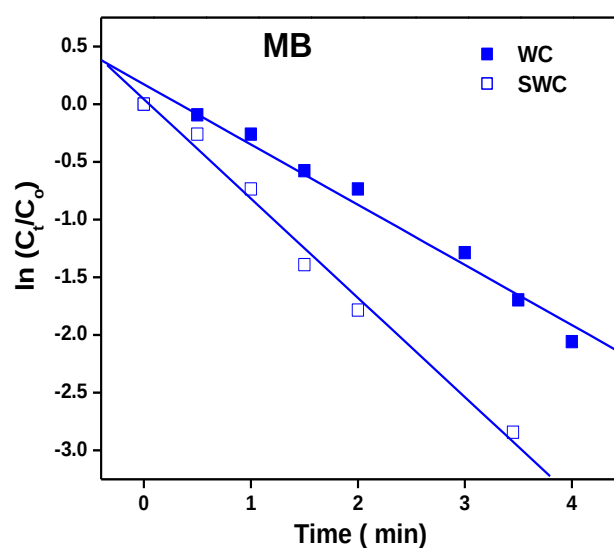


Figure 7: Plots of $\ln C_t/C_0$ versus reaction time (min) for the MB dye reduction

5. Interpretation of Results

5.1. X-ray diffraction (XRD) analysis

Figure 2 illustrates the XRD patterns for WC and SWC samples. The XRD pattern shows broad peaks, indicating low crystallinity and tiny crystalline areas within the sample. Broad XRD peaks indicate an amorphous structure with trace amounts of crystalline cellulose (Zuluaga et al., 2024, 5866). The observed pattern shows how cellulose, hemicellulose, lignin, and oils contribute to the structure of WC (Ballesteros et al., 2014, 3493–3503). The diffraction peaks at 16.5° and 20.0° are thought to be the distinctive signals of cellulose, and the broader peak at about 34.5° verifies the presence of hemicelluloses (Lee et al., 2024, 121181). The XRD of WC and SWC was the same, which indicated that the ultrasonic treatment doesn't effect on the phase structure of WC. The broad peaks in the X-ray diffraction pattern show that the samples possess small crystallite sizes (Naghmash et al., 2022, 103532). However, as can be observed, the ultrasonic treated WC diffraction peaks showed less intensity, suggesting lattice deformation and a smaller crystal size (Yan et al., 2025, 107333).

5.2. FTIR analysis

The FTIR spectra is used to determine the functional groups of the produced materials. Figure 3 displays the FTIR spectra of CW and SCW samples in the region of 4000 to 400 cm^{-1} . The FTIR study revealed a

wide band at 3473 cm^{-1} , indicating bound –OH groups on the surface of WC. Molecular hydrogen bonding of polymeric substances, including alcohols, phenols, and carboxylic acids, as found in pectin, cellulose, and lignin, is responsible for the broad band (Iqbal et al., 2009, 161–171) (Gnanasambandam and Protor, 2000, 327–332). The peaks at 2923 and 2854 cm^{-1} result from C–H vibration. The adsorption peaks at 1743 cm^{-1} correspond to carboxyl linkages from xanthenes derivatives, such as caffeine (Kaikake et al., 2007, 2787–2791). Absorption bands at 1645 and 1466 cm^{-1} indicate the presence of carboxyl (COO) and C–O groups. Bands at 1384 cm^{-1} represent COO–symmetric stretching vibrations. An additional absorption band that appears at approximately 1165 cm^{-1} may be related to the C–O stretching (Lafi et al., 2014, 2198–2206). The peak at about 870 cm^{-1} caused by the stretching bond of C–N (Ayalew and Aragaw, 2020, 205–222).

5.3. Catalytic reduction of dyes

The ability of waste coffee samples to reduce highly hazardous pollutants (organic dyes) like Methylene Blue (MB) and Remazol Red (RR) was examined. For RR and MB, the dye's distinctive maximum absorption peaks are located at 520 and 664 nm , respectively. The time-dependent absorption spectra of RR and MB reduction with NaBH_4 alone and NaBH_4 with catalyst (WC & SWC) are shown in Figures 4 and 5, respectively. It has been established that dye reduction is impossible without NaBH_4 . It has been

shown that NaBH_4 is necessary for the dye reduction process. When NaBH_4 is present alone without a catalyst, the dyes require an incredibly long time to be reduced, indicating an incredibly slow rate of reduction without a catalyst (Naseem et al., 2019, 855–864). Moreover, using NaBH_4 without waste coffee samples it takes 120 minutes for MB and 9 minutes for RR to reduce dyes. This suggests that while reducing dyes in the presence of NaBH_4 is a thermodynamically favorable reaction, it is kinetically unfavorable because the reactants (dyes and NaBH_4) have a large energy barrier that prevents a rapid reaction. In order to overcome the energy barrier and accelerate the rate of reaction, a catalyst was used (Naseem et al., 2020, 124646). According to Figures 4 & 5 it was illustrated that in the existence of NaBH_4 , RR dye total reduction happened at 2.33 min via using waste coffee sample (WC), 1.53 min using sonicated waste coffee sample (SWC). Furthermore, MB dye complete reduction occurred at 4.05 minutes using WC and 3.45 minutes using SWC in the presence of NaBH_4 . The catalyst's function is to accelerate the rate at which NaBH_4 hydrolyzes, so it increases the rate of reaction (Naseem et al., 2024, 6372). Furthermore, the reduction of dyes occurs significantly more quickly when SWC is employed in the presence of NaBH_4 than when WC is utilized. In general, the cavitation of ultrasound was responsible for the effectiveness of ultrasonic chemical reactions (Wang et al., 2019, 273–278). Many tiny bubbles were created when a liquid was exposed to a specific level of

ultrasonic radiation. The development, vibration, growth, and constriction of these tiny bubbles results in a series of physical and chemical changes that ultimately lead to their collapse, this effect is known as cavitation (Soltani et al., 2018, 373–382). A significant amount of energy was released both inside and outside the cavitation bubble as it collapsed (Jorfi et al., 2018, 95–107) which enhances the catalytic activity of the catalyst. It has been demonstrated that ultrasonic preparation techniques increase the catalytic activity of a variety of catalysts by improving active site dispersion, reducing particle size, and altering surface characteristics. Using ultrasound during the production of catalysts can result in smaller, more homogeneous catalyst particles, increasing their surface area and the number of active sites available for catalytic processes (Zhang et al., 2021, 105466). According to these results, sonicated treated waste coffee showed higher reduction activity than normal treated waste coffee.

5.4. Kinetic study

The kinetics study was carried out to determine the reaction rate constant using a pseudo-first-order model (Abay et al., 2017, 5628–5638). The following relation is used:

$$\ln(C_t/C_o) = -kt \quad (2)$$

The symbol in this equation has the following definition: k is the rate constant, C_o is the dye starting concentration, and C_t is the dye concentration at a specific time (t). The relationship between time (t) and $\ln(C_t/C_o)$ can be plotted to get the rate constant

from the slope. Figures 6 & 7 showed the linear fitting data for RR and MB dye reduction, respectively, using two different catalysts. Table 1 contains the calculated rate constant data. Table 1 and Figures 6 & 7 suggest that SWC reaction rate was higher than WC, due to the large number of active sites on SWC (Zhang et al., 2021, 105466). Equation 3 was used to calculate the reduction efficiency (Oliveira et al., 2024, 11994), and Table 1 provided the data.

$$\text{Reduction efficiency} = \frac{(A_0 - A_t)}{A_0} \times 100 \quad (3)$$

where A_t denotes the absorbance at equilibrium time and A_0 denotes the absorbance at time $t = 0$ min (before to the catalyst addition). It was explained that adding waste coffee and sonicated waste coffee improved the reduction efficiency for dyes. It was concluded that the reduction efficiency of the waste coffee samples towards RR dye is higher than MB dye.

5.5. Mechanism of catalytic reduction

With a catalyst present, NaBH_4 molecules are introduced to the reaction medium as a reducing agent. NaBH_4 is well-known for its potential as a hydrogen source. When NaBH_4 is hydrolyzed, sodium ions (Na^+) and borohydride ions (BH_4^-) are initially liberated in water immediately. While the liberated electrons were moved to the catalyst surface, BH_4^- will then electrostatically adsorb to the waste coffee surface and react with water to produce borate (BO_2^-) and hydride (H^+) ions. The

catalyst transfers electrons from the donor (BH_4^-) to the acceptor (organic dyes) by functioning as an electron relay mechanism. The adsorption of dyes onto the surface of waste coffee occurs at the same time. A hydrogen atom created by the BH_4^- ions attacks the nearby dye molecule after an electron transfer, and the dyes are concurrently hydrogenated as a result of the electron transfer. Finally, the reduction of dyes has occurred. The catalyst's electrons and the H^+ from BH_4^- have a synergistic effect that affects the reduction processes. The end product of the reduction process will desorb from the waste coffee surface, freeing up space for more catalytic reduction (El Boraei et al., 2025, 105486), (Naghmesh and Ibrahim, 2022, 126036).

6. Conclusion

Waste coffee was collected from the house and treated with simple and ultrasonic method. The activity of the treated samples was examined in the field of wastewater treatment. Reduction of Remazol Red (RR) and Methylene blue (MB) dyes using NaBH_4 as reducing agent was established. Waste coffee samples showed great reduction efficiency towards dyes reached maximum 95.57 % using sonicated waste coffee for RR dye. Because of the reduced particle size, increased surface area, and increased dispersion of active sites on the sample surface, the ultrasonic treated sample exhibited more activity than another treated

sample. Waste coffee materials offer an environmentally friendly and promising way to remove dyes from wastewater. With further research and development, waste coffee could become a viable alternative to traditional methods, promoting ecologically friendly water treatment techniques.

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