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GREEN SYNTHESIS OF COPPER OXIDE NANOPARTICLES TO HARVEST THE LIGHT FOR PHOTOCATALYTIC DEGRADATION OF DYES METHYLENE BLUE AND METHYL ORANGE

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ABSTRACT. This research (preliminary study) aims to explore the green synthesis approach and characterizations of copper oxide nanoparticles, which employed to photocatalytic degradation of methylene blue (MB) and methyl orange (MO) from aqueous solution. *Centella asiatica* fresh leaves were used in the green synthesis of copper oxide (CuO) nanoparticles (NPs) because it contains multifunctional properties like reducing agent as well as stabilizing agent. The copper oxide nanoparticles were synthesized at ambient temperature and pressure, furthermore it was characterized by scanning electron microscopy (SEM) and thermal gravimetric analysis (TGA), which confirmed their thermal stability, and surface morphology. The photocatalytic efficacy of CuO was investigated against MB and MO. Experiments were conducted at different temperature with aid of Pyrex reactor where degradation efficiency was examined through UV-Visible spectrophotometer. Analysis confirmed that, it was Pseudo first order degradation whereas activation energy calculated were 26.19 kJ/mol and 32.6 kJ/mol for M.O and M.B respectively. Factors such as initial concentrations of dye, temperature, does of catalyst, and rate of agitations were optimized to determine how these factors contribute the efficiency of degradation. The CuO nanoparticles showed excellent property as heterogeneous catalyst and retained same behavior after multiple use. The results showed that the green synthesis of CuO NPs is promising due to inexpensive, greener process to decontaminate the dye-wastewater. This study explores the sustainable approach to synthesized green catalyst and addressing the removal of dye to mitigate the environmental remediation.

Graphical Abstract

INTRODUCTION

In recent few decades, metal oxide nanoparticles (NPs) emerged as one of promising type of transition metal oxide due to their superior electrical and thermal conductivities, unique physicochemical characteristics, and wide range of applications in the fields of catalysis, sensing, energy storage, and environmental remediation (Huang, He et al. 2019, Ali, Nabeel et al. 2023). Among various metal oxides, CuO is one of the most famous examples of a p-type semiconductor with a narrow bandgap (1.2 eV) that has been used in both redox and photocatalytic reactions as a highly efficient heterogeneous catalyst. Factors such crystal planes, surface oxygen lattice, and morphology influencing catalytic performance of nanostructures and for technological applications require controlled synthesis of size- and shape-specific nanostructures (Aazam, Mohamed et al. 2013). One of the most significant applications of CuO NPs lies in the photocatalytic degradation of organic pollutants, especially synthetic dyes such as methyl orange (MO) and methylene blue (MB) (Acedo-Mendoza, Infantes-Molina et al. 2020). Photocatalysis is initiated when visible or UV light promotes electrons from the valence band to the conduction band of a semiconductor catalyst, producing electron-hole pairs (Affandi, Joseph et al. , Qasim, Manzoor et al. 2026). These charge carriers further interact with molecular oxygen and water to generate highly reactive species such as hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet -}$) (Arif, Rasheed et al. 2026, Joseph, Anisuzzaman et al. 2026). These radical species have the potential to mineralizing organic pollutants into non-toxic end products such as H_2O and CO_2. Advanced oxidation processes (AOPs) is emerged as superior alternatives to conventional methods due to their ability to degrade a wide range of toxic compounds into less harmful or completely benign substances (Abboud, Saffaj et al. 2014, Nabeel, Hussain et al. 2025).

The industrial effluents are usually toxic and may contain heavy metals (Hg, Cr, Cd, As, Pb), nitro aromatics, phenolic derivatives, pesticides and dyes, all of them are very dangerous to the human body and aquatic environment (Qasim, Manzoor et al. 2025, Arif, Rasheed et al. 2026). Heterogeneous photocatalysis, which involves the application of semiconductor oxides (CuO, V_2O_5, TiO_2, SiO_2, CdS, Fe_2O_3, SnO_2, ZnS, BiOI, ZnO etc) has been shown to be a cost effective and efficient way of dealing with these pollutants using redox transformations (Nabeel, Hussain et al. 2025). Among these, the most

appealing is CuO owing to its low cost, narrow bandgap and high catalytic properties, thus making it very effective in degradation of dyes using visible light. Sol-gel processing, hydrothermal treatment, gas-phase deposition, microwave-assisted synthesis, thermal decomposition, and combustion techniques are the conventional techniques of synthesizing CuO nanoparticles.

Although such physicochemical methods offer controlled nanostructures, they are usually expensive, energy intensive, and the processes involved come with dangerous byproducts, which restrict their application in the environment at large scale. Therefore, the green synthesis approaches are also developed with much momentum and gaining attention (Bhattacharjee, Ahmaruzzaman et al. 2018). Green synthesis strategies employ biological resources like algae, microorganisms, and especially plant extracts that also serve as reducing, stabilizing and capping agents (Arif, Rasheed et al. 2025). Plant-mediated synthesis is also useful in that it does not use toxic chemicals, less energy is required, and the nanoparticles obtained are uniform and more stable than most chemical methods (Khan, Moeid et al. 2025). The phytochemicals in the plant tissues contain alkaloids, terpenoids, flavonoids and polyphenols, which have the ability to regulating the growth of the particles as well as reducing the metal salts to nanoparticles(Dauthal, Mukhopadhyay et al. 2016, Vaseghi, Nematollahzadeh et al. 2018). In traditional medicine, *Centella asiatica (L.),* also called as Gotu kola, has been extensively known to possess medicinal properties and to contain high levels of bioactive compounds. In this experiment, the *C. asiatica* leaves extract was utilized which act as a reducing agent as well as a stabilizing agent in the synthesis of the green synthesis of CuO NPs in the presence of copper acetate [$Cu(CH_3COO)_2$] as a precursor(Chandrika, Kumara et al. 2015, Sabaragamuwa, Perera et al. 2018).

The current project (preliminary study) is planned to be engineered with the goal of designing cost-effective, an effective, and sustainable photocatalyst to decompose harmful organic dyes in water. In this respect, the synthesis of copper oxide nanoparticles was conducted in green and a simple procedure by utilizing the *Centella asiatica* leaf extract that acted both as a stabilizing and reducing agent. The objective was to develop a synthesis pathway that utilizes readily available and cheap precursor materials at standard temperature and pressure, and thus, reduces the cost of reaction. The current paper is able not only to demonstrate the benefits of plant-mediated synthesis to obtain well-defined and stable copper oxide nanoparticles, but also explore their practical use in the decolorization and degradation of model organic dyes including methylene blue (MB) and methyl orange (MO) (Chaudhary, Rohilla et al. 2019). This paper also discusses the operational parameters required to achieve the maximum degradation efficiency of MB and MO. Through environmentally sustainable processes, these types of research help to develop green technologies aimed at pollution removal. Such an approach promotes sustainable environmental management of several United Nations Sustainable Development Goals (SDGs), particularly SDG 6, SDG 9, and SDG 12 (Ibrahim, Joseph et al. 2025).

MATERIALS AND METHODS

The study was carried out at the Chemistry Department, Government College University, Faisalabad and detailed characterization was done at the National Textile University, Faisalabad. The objectives of the research were synthesis and characterization as well as photocatalytic degradation of methyl orange (MO) and methylene blue (MB) dyes by employing copper oxide (CuO) nanoparticles in aqueous solutions. The analytical grade chemicals that were used in all experiments were not further purified to ensure the reproducibility and reliability of the findings. Copper acetate [$Cu(CH_3COO)_2$] was used as the precursor material and distilled water was used in all the solutions. MB and MO dyes were purchased from Merck, Germany. Centella asiatica fresh leaves collected from Jaranwala were used to because it contains the bioactive phytochemicals such as, flavonoid, terpenoids, and polyphenols, which has natural ability to reduce and stabilize nanoparticle formation. The extract of the plant involved washing and then shade drying of the leaves over a period of thirty days. The leaves were then dried and refluxed in 700 mL of the distilled water for two hours; the leaves then separated and the filtrate then collected

through standard filter paper. This aqueous extract was used directly in the green synthesis of CuO nanoparticles, which offered a new green and sustainable gateway alternative to the traditional chemical procedures.

Synthesis of CuO NPs

For the synthesis of CuO NPs, 4.57 g of copper acetate was dissolved in 250 mL distilled water to make a 0.1 M solution. Followed by this, 30 mL was transferred from this solution into another beaker, and 50 mL of the plant extract was added drop by drop into the solution under constant magnetic stirring over a period of 2 hours at ambient temperature. The dropwise addition of plant extract ensured controlled nucleation and uniform growth of nanoparticles. The attained mixture was centrifuged and then the obtained precipitate was washed with ethanol and distilled water to eliminate unreacted precursors. The dried nanoparticles were first dried at 80°C and further calcined at 600°C to produce crystalline CuO nanoparticles with intended photocatalytic characteristics. **Figure 1** shown the representation green synthesis of CuO nanoparticles using the *Centella asiatica* (used as source of stabilizing and reducing agents). These bioactive compounds in the leaves allow the process of green synthesis, which involves the reduction of copper ions to nanoparticles and capping them to avoid from agglomeration.

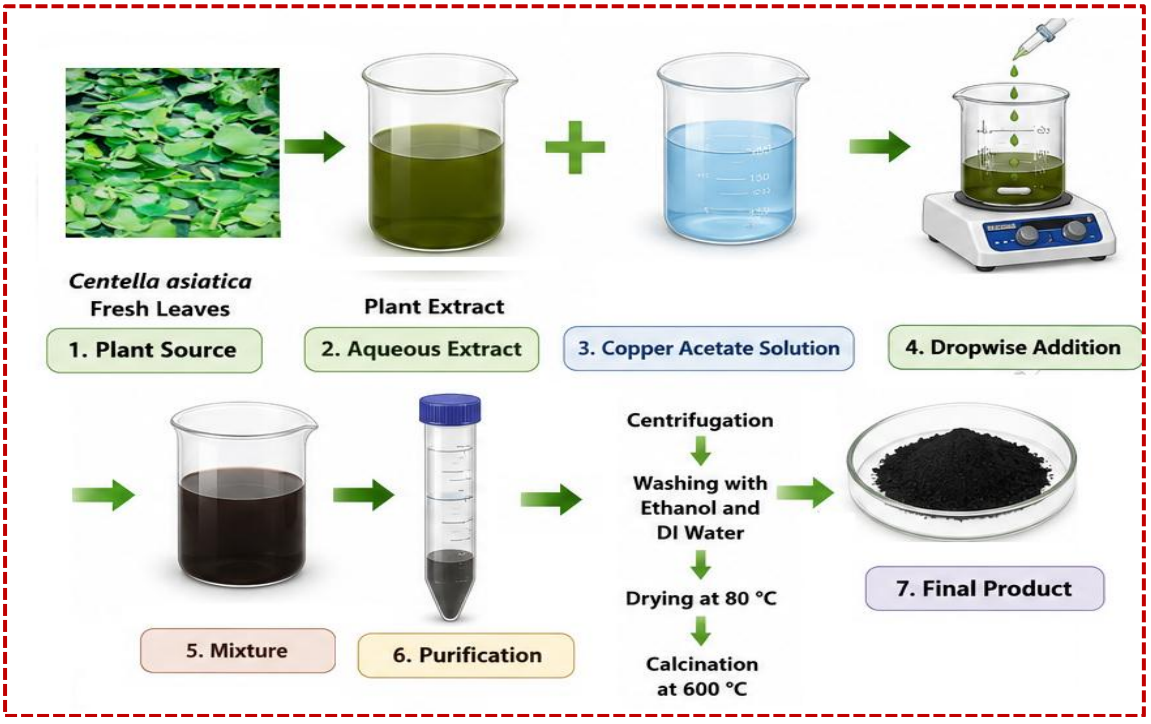

Figure 1. Schematic representation of the green synthesis of CuO nanoparticles using the Centella *asiatica* fresh leaves acted as source of a stabilizing and reducing.

Photocatalytic test:

To evaluate the catalyst efficiency, experiments of photocatalytic degradation were conducted in test beakers of 500mL using aqueous solution of MO and MB dyes at different concentration and stirring the mixture at 500rpm at different temperatures. First, 0.5 mL of the dye solution was sampled after 30 minutes of dark stirring to assess adsorption desorption equilibrium. This was followed by the addition

of 0.05 g of CuO nanoparticles and stirring in the dark for more 30 minutes and then UV light was irradiated on the mixture (Ilyas and Saeed 2011, Jia, Mei et al. 2012). The photocatalytic degradation efficacy of MO and MB was check over time by taking aliquots of the reaction mixture, diluting it with 10 mL of distilled water, and measuring it by UV-Visible spectrophotometry using 1 cm path-length cuvettes. Calibration curves were used to find dye concentrations, and percentages of dye degradation were determined by using formula (Moon, Salunke et al. 2018, Mosleh, Rahimi et al. 2018).

$$\textbf{Degradation \%} = C_o - C_t / C_n \quad X\ 100 \qquad (1)$$

In this equation, C_o represents the initial concentration, while C_t the concentration at time t. This systematic sampling made it possible to assess kinetic analysis and reaction rate evaluation, which would be reproducible and reliable data to determine photocatalytic efficiency.

RESULTS AND DISCUSSION

Characterization of CuO Nanoparticles

SEM Analysis: The size distribution and morphology of the prepared fabricated copper oxide (CuO) Nanoparticles was analyzed using the scanning electron microscopy (SEM). The homogeneous and almost spherical particles with low aggregation/ uneven surface is observed (indicating the successful deposition and formation of nanoparticulate clusters), are seen in the SEM images as shown in **Figure 2a-d.** The particle size was determined to be in the sub-micron (with increasing magnification,), which justified the synthesis of nanoparticles. This morphology (the development of granular and more defined nanostructures becomes evident) reflects that the green synthesis procedure with *Centella asiatica* extract is useful in regulating the particle growth and agglomeration (revealing the progressive nucleation and growth of CuO nanoparticles). This surfaces exhibit a high surface area, which is essential in the catalytic applications, increasing the number of active sites that can be used in the reactions of degrading dyes. Well-dispersed particles make sure that the maximum contact of the dye molecules takes place in the process of photocatalysis, which may boost up the degradation efficiency (Nezamzadeh-Ejhieh and Karimi-Shamsabadi 2013, Nasrollahzadeh, Sajjadi et al. 2018). The SEM analysis demonstrated that the green synthesis approach produces specific form of shape and size (nano-clusters with rough textures which is essential to the photocatalytic activity (Chowdhury, Khan et al. 2020, Aroob, Carabineiro et al. 2023)) of the CuO nanoparticles and these structural properties reflect to high catalytic performance that are consistent adsorption sites and the development of effective electron-holes generation at the UV light.

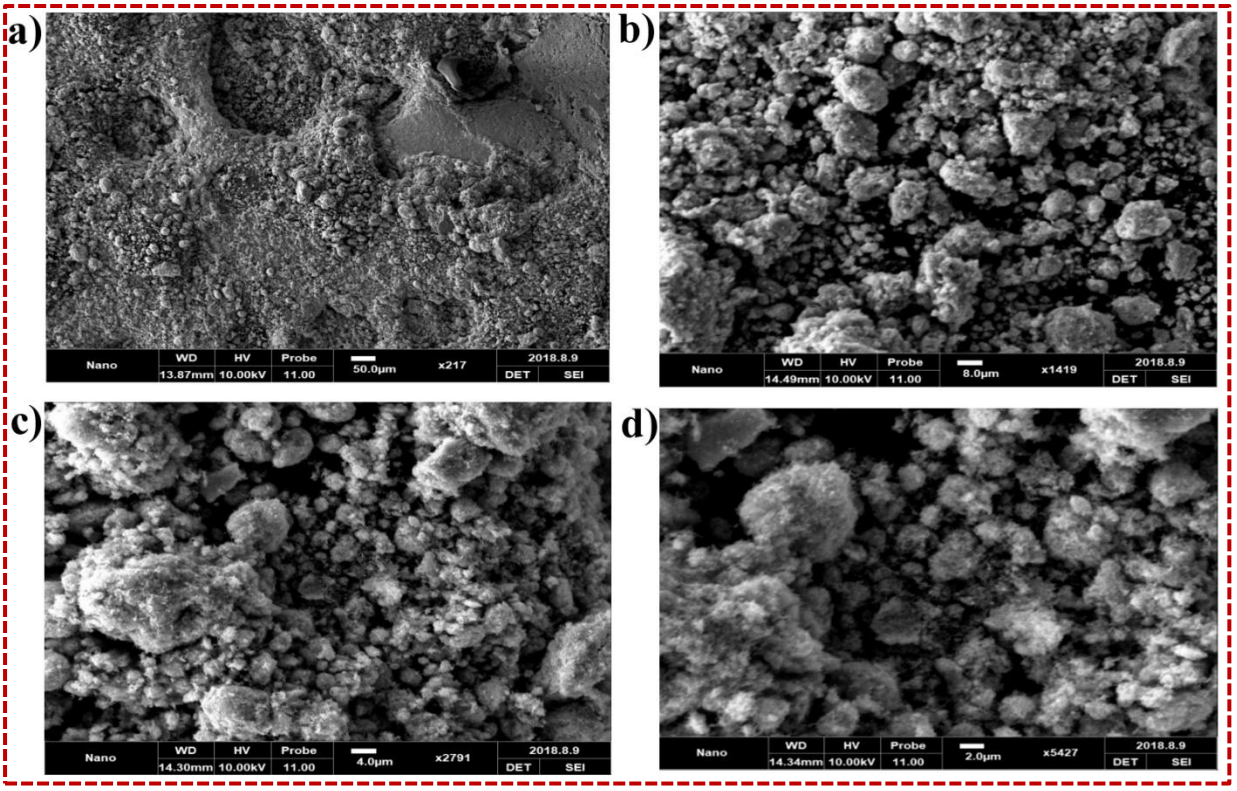

Figure 2: (a-d) SEM photographic images of fabricated copper oxide (CuO) Nanoparticles

Thermogravimetric Analysis (TGA): TGA was carried out to examine the thermal stability of fabricated copper oxide (CuO) Nanoparticles as illustrated in **Figure 3 (**exhibited a gradual weight loss of approximately 2.9% from 30 to 500°C**).** Analysis suggests that there was an initial weight loss to below 150°C, was attributed to the removal of adsorbed moisture. While the subsequent loss between 150 and 400°C was attributed to the decomposition of phytochemical residues (from the *Centella asiatica* plant extract). Above this 500°C temperature, the catalyst demonstrated remarkable stability (the mass remained nearly constant), indicating the formation of thermally stable CuO nanoparticles with minimal residual organic content and this implies its use in high temperature applications. The low weight loss at high temperatures implies that the structural integrity of the nanoparticles is not degrade during catalytic functions (Kana, Kaviyarasu et al. 2019, Saeed, Muneer et al. 2019). One important parameter of the heterogeneous catalysts is that the material is thermally stable so that it can sustain repeated heating cycles without structural deformation. TGA findings show that the nanoparticles of CuO synthesized through green procedures are thermally stable, and their excellent thermal stability at elevated temperatures helpful in photodegradation reaction in diverse environmental conditions (Sajjad, Ullah et al. 2018).

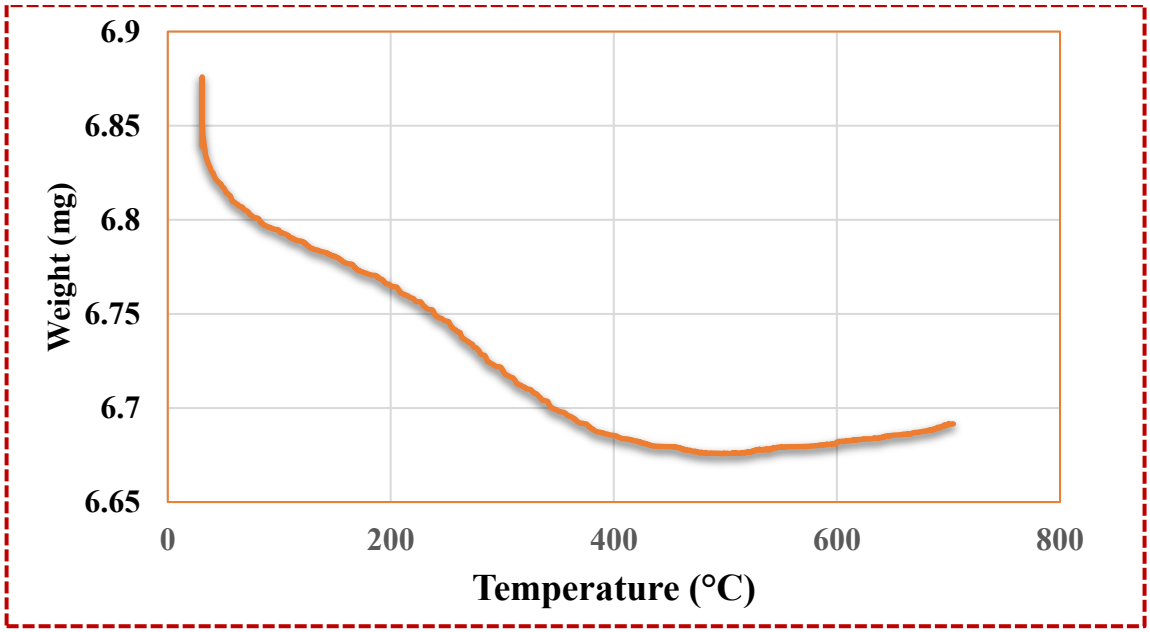

Figure 3. TGA analysis of fabricated copper oxide (CuO) Nanoparticles

Photocatalytic Degradation of Methylene Blue Dye

Analysis of Reaction Mixture: The photocatalytic experiments were conducted to determine the concentration of M.B by using UV-Vis spectroscopic analysis. Standard solutions of 10 -50 ppm were made and their absorbance spectra were measured as illustrated in **Figure 4 (a).** The peak at 505 nm represents the λmax. Therefore, all absorbance measurements during the photocatalytic degradation experiments were carried out at this 505 nm wavelength. **Figure 4 (b).** demonstrated the calibration curve that was prepared by drawing a graph between the concentration and the absorbance, which could be used to find the dye concentration at different times during the degradation process (Salavati-Niasari and Davar 2009). The calibration curve showed excellent linearity ($R_2 > 0.998$), which confirmed the accuracy of the absorbance measurements to quantify the sample. This method ensures that a reduction in absorbance in the course of catalytic experiments can be attributed directly to the dye degradation as opposed to experimental artifact. Calibration is important in the determination of kinetic parameters and the effective assessment of the CuO nanoparticles as photocatalyst as shown in **Figure 4 (b).**

Impact of Catalyst Dose: The effect of the loading of catalysts on the degradation of M.B was investigated by taking different dose of catalysts CuO (0.05 g to 0.25 g) per 100 ml was shown in **Fig 4(c).** The dose of the catalyst peaked the degradation efficiency to a point of 0.2 g, after which it showed

a slow decline. This is because the rate of degradation was higher at lower doses may suggests that there are more active sites available to form the reactive oxygen species (ROS) and dye oxidation. The drop on higher dose is probably because of light scattering causes less absorption and weak penetration of photons through the suspension, which has an increased turbidity (Sankar, Manikandan et al. 2014). These findings suggest that there is an optimum catalyst loading at which the photocatalytic efficiency is highest. The measured trend is consistent with the heterogeneous photocatalysis mechanism, in which surface adsorption of dye molecules and electron-hole pairs formation are the key factors. High dose of catalyst may be counterproductive to light penetration thereby reducing the efficient photocatalytic reaction.

Analysis of the effect of agitation speed on degradation: The influence of stirring speed on M.B degradation was monitored in the range of 100-600 rpm at 40 °C using 0.2 g of CuO as demonstrated in **Fig 4(d).** The rate of degradation plateaued and starting at 400 rpm, then declined. The optimal stirring rate provides good dispersion of the catalyst and mass transfer of the dye molecules to the active sites of catalyst effectively. Extreme agitation can cause less time of contact between the dye molecules and the catalyst surface leading to lower degradation efficiency. The agitation studies emphasize the significance of optimization of reaction conditions in the process of efficient photocatalysis. Effective stirring is also used to increase catalyst-dye contact as well as to prevent the agglomeration of nanoparticles leading to sedimentation of a reaction. These findings are essential in the scaling up of the process to be applicable in real wastewater treatment.

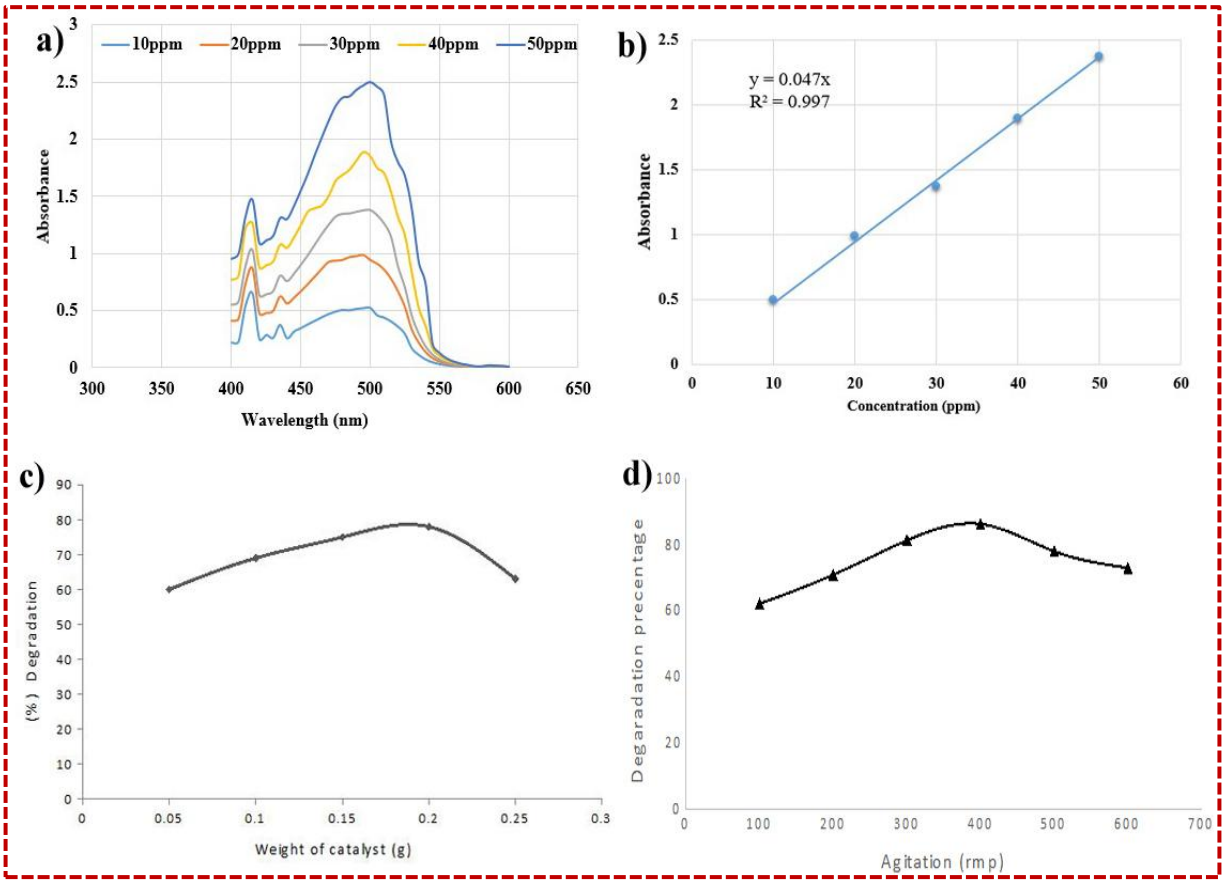

Figure 4. a) Visible range spectra of different standard solutions of M.B recorded b) Calibration curve for dye Methylene Blue (M.B) showing excellent linearity c) Impact of catalyst dose on the dye's degradation efficacy d) Impact of agitation on percentage degradation of M.B dye.

Impact of Temperature on degradation: Impact of temperature on photocatalytic degradation were tested at 30°C, 40°C and 50°C as illustrated in **Figure 5(a).** The rate of degradation was increased by rise in temperature with the degradation efficiencies reached near about 72%, 86%, and 90% at 30, 40,

and 50°C, respectively .Raised in temperatures increase the number of molecular collisions therefore, the rate of production of ROS and the kinetics of dye degradation (Sathishkumar, Sweena et al. 2011, Senobari, Nezamzadeh-Ejhieh et al. 2018). Temperature-dependent behavior confirmed that the photocatalytic process is endothermic means energy need to proceed the reaction (which promote the photocatalytic oxidation of MB molecules). High temperatures not only increase the rate at which dye molecules diffuse to active sites as well as increase the mobility of charge carriers in the catalyst, thus increasing the overall reaction rate. These studies give an insight into thermal stability and the efficiency of CuO nanoparticles to perform photocatalytic reactions.

Impact of Dye Concentration: The effect of higher concentration of Methylene Blue (M.B) on degradation efficiency was investigated by the use of 100, 200, and 300 ppm solutions as illustrated in **Figure 5(b).** The analysis indicates that higher dye concentration loading leads to decrease the percentage degradation. On the catalyst surface, the active sites become saturated at higher concentrations resultantly, photon absorption is decreased, which limit the generation of ROS. In the case of 100 ppm solution, 87% degradation was observed, while only lower degradation efficiencies of about 67% and 62% were obtained for 200 and 300 ppm (Song, Zhou et al. 2008). This is a concentration dependent effect, which highlights that photocatalytic activity is highly sensitive to initial dye loading. These lower concentrations enable the photons to easily penetrate and interact more with the catalyst active sites to a greater extent resulting in higher degradation. These insights are essential in designing treatment plans of wastewater that have different loads of pollutants.

Kinetic Studies of Methylene Blue Degradation: The photocatalytic degradation efficiency of M.B was also examined (Kinetic analysis at different temperatures) by using the pseudo-first-order kinetic model. The data of time-dependent concentration at various temperatures (30, 40, 50°C) were plotted as per this equation as shown in **Figure 5(c).** The resulting linear plots ensured that the reaction is pseudo-first-order in nature. The linear relationship between $\ln(C_0/C_t)$ and irradiation time confirms the applicability of the Langmuir–Hinshelwood model. The consistency in the following of pseudo-first-order behavior is confirmed by the linear correlation ($R^2 > 0.995$), which means that the degradation rate is directly proportional to the dye concentration. This kinetic study gives an understanding of the catalytic mechanism in terms of the rate-limiting step, which is the interaction of the dye molecules and the photogenerated reactive oxygen species at the catalyst surface. It is supported by the data, determined the temperature-dependent rate constants presented in **Table 1** and they are a quantitative indicator of the efficiency of the catalyst under different thermal conditions. **Figure 5(c)** and **Table 1** has been used to calculate rate constants (k) and shows that there is an evident increase in rate constant with temperature. At 30 °C, k = 0.0221 min^{-1}; at 40 °C, k = 0.0298 min^{-1}; and at 50 °C, k = 0.0421 min^{-1}. This tendency suggests that the increased rate of reaction owing to high-speed collisions between molecules and to the high speed of charge carrier's movement in high temperatures (indicating that higher temperatures facilitate the degradation process and enhance the reaction kinetics). The temperature dependence observed is expected to be aligned with a behavior of the Arrhenius-type, which proves the fact that the photocatalytic degradation of M.B is thermally activated. This kind of kinetic data is essential to the optimization of operation parameters and process scaling when it comes to industrial wastewater treatment.

Table 1. Rate constant determined by applying to the degradation data at various temperatures.

Temperature (°C)	k= min^{-1}
30	0.0221
40	0.0298
50	0.0421

Concentration-Dependent Kinetics: M.B was also applied to the pseudo-first-order model (Kinetic analysis at different dye concentrations). **Figure 5(d)** exhibits the M.B degradation in various initial concentration (100, 200, 300 ppm) at constant temperature (30°C) in the presence of 0.1 g CuO.

The model was once again confirmed by linear fits. Rate constants has opposite relationship with the dye concentration: 0.1145 min^{-1} (100 ppm), 0.0678 min^{-1} (200 ppm), and 0.0521 min^{-1} (300 ppm), with corresponding R^2 values of 0.8758, 0.9002, and 0.8052. which are summarized in **Figure 5(d)** and **Table 2.** The highest rate constant was observed for the 100 ppm solution, (faster degradation kinetics at lower dye concentrations) and suggests that excessive dye molecules hinder light absorption and occupy active catalytic sites. This behavior attributes to saturation of catalyst active sites and decreased photon penetration at high dye loads leading to a lower number of effective ROS interactions occurring per dye molecule. This demonstrates the need to optimize the pollutant concentrations in order to maximize the photocatalytic effectiveness.

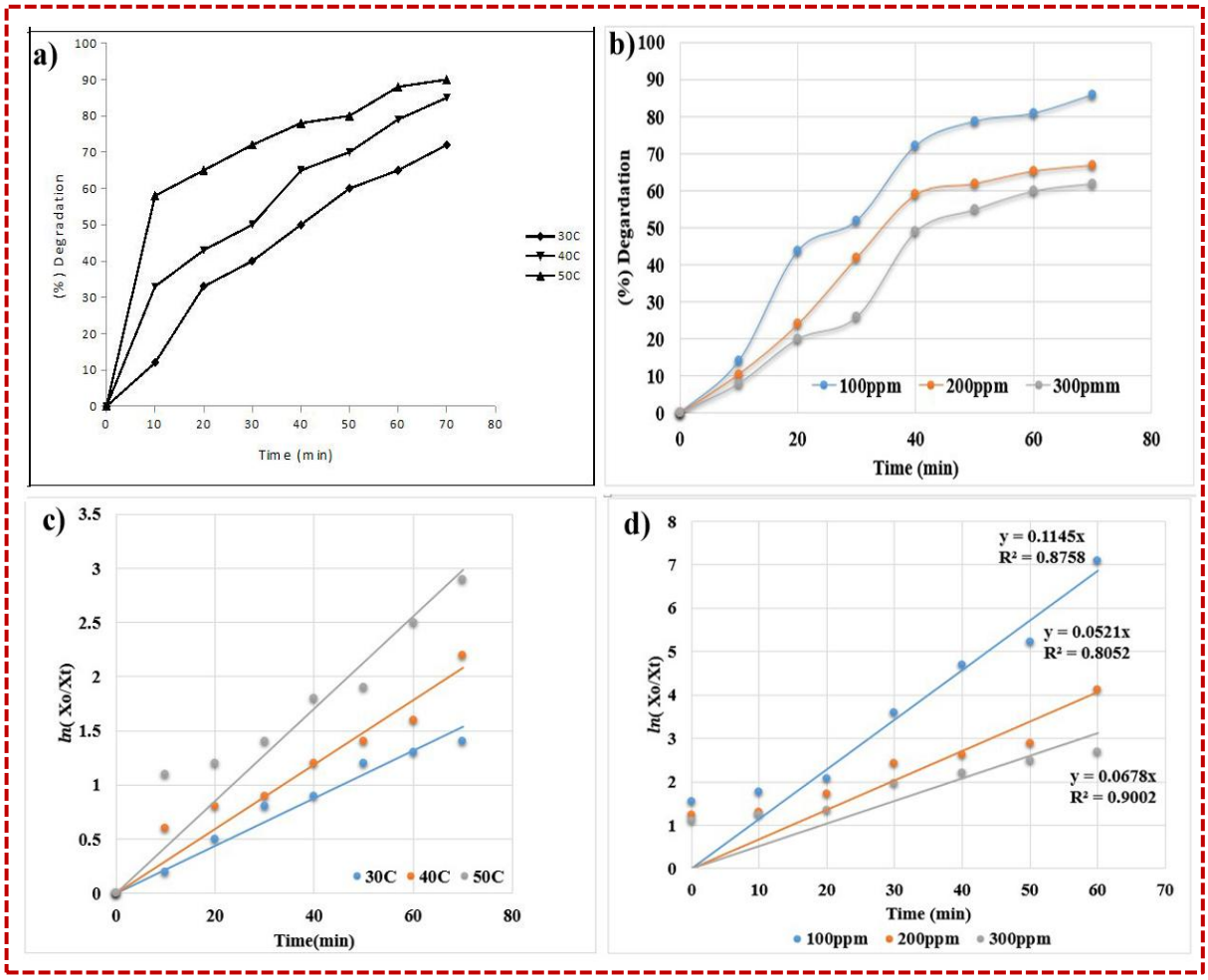

Figure 5. a) The influence of temperature on degradation efficiency of Methylene blue *Centella asiatica*-mediated CuO nanoparticles b) Impact of concentration of M.B dye on percentage degradation efficiency c) Pseudo-first-order kinetic plots at at varying temperatures. d) Pseudo-first-order kinetic plots at various dyes concentration.

Table 2: Degradation data at different concentrations was used to find the rate constant for MB.

Concentration (ppm)	K= min^{-1}
100	0.1145
200	0.0678
300	0.0521

Arrhenius Analysis:

To find the activation energy of the degradation process against temperature, the rate constants of degradation process were used to plot an Arrhenius plot as shown in **Figure 6.** Arrhenius plot of ln(k) versus 1/T, which exhibited excellent linearity with a correlation coefficient (R^2) of 0.996.

The value of the activation energy, which was calculated, is 26.19 kJ mol^{-1}, implying that the energy barrier to the electron-hole generation and oxidation of the dyes with the support of ROS is moderate. The value of such is comparable to the typical semiconductor photocatalysts, and reflects the efficacy of CuO nanoparticles in UV/visible light. The kinetic and thermodynamic data both support the statement that the photocatalytic degradation of M.B by CuO nanoparticles is a first-order, temperature sensitive process, which is driven by surface interactions and generation of reactive species. Moreover, the strong linear correlation confirms that the degradation process follows Arrhenius behavior within the investigated temperature range (temperature plays a significant role in enhancing the photocatalytic performance and accelerating the degradation kinetics of methylene blue). These insights play a critical role in the systematic development and optimization of photocatalytic systems of water treatment.

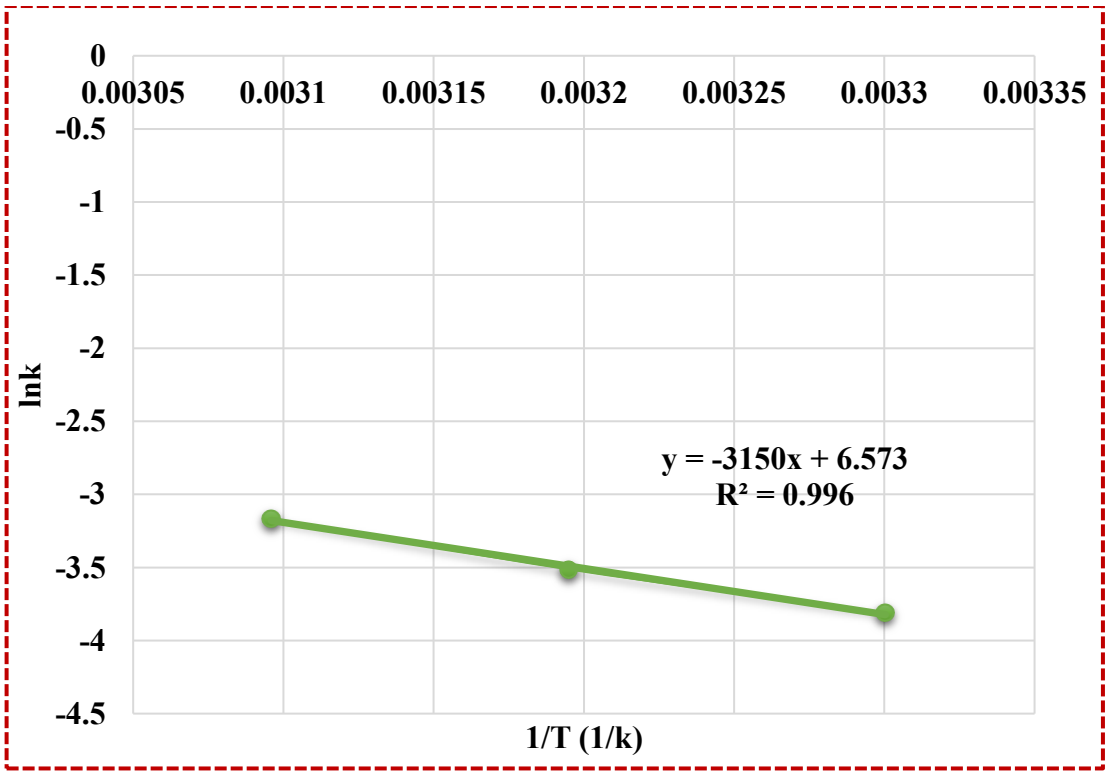

Figure 6: Arrhenius plot of ln(k) versus 1/T for the photocatalytic degradation (using *Centella asiatica*-mediated CuO nanoparticles).

Photocatalytic Degradation of Methyl Orange (M.O)

Analysis of Reaction Mixture: Firstly, the standard solutions of M.O solutions at different concentrations

(10–50 ppm), and their absorbance spectra were monitored through spectrophotometer within 400–600 nm range which is known as visible range. The λ max at 475 nm was observed (indicating adherence to the Beer–Lambert law) for M.O as demonstrated in **Figure 7(a).** The resulting calibration curve, shown in **Figure 7(b)**, displayed the excellent linearity and concentration over the investigated range with the regression equation **y = 0.0463x** and a correlation coefficient **R^2 = 0.9982**, enable accurate determination of M.O concentrations at various reaction times. The UV- Vis spectra validate distinct absorption properties of M.O, justifying the analysis technique of degradation and kinetic investigations. The dye concentration at different times was determined using calibration data, which is necessary to measure photocatalytic performance.

Impact of Catalyst Dose: The impact of catalyst loading (0.05-0.25 g) on M.O having 200 ppm concentration at 40 °C were investigated which were demonstrated in **Figure 7(c)**. The optimum catalyst dose was found to be at maximum degradation when 0.2g of catalyst was used (The degradation efficiency initially decreased with increasing catalyst dose up to 0.15 g, then increased to a maximum at 0.20 g suggesting an optimum catalyst loading for effective photocatalytic degradation). An increase in catalyst amount led to reduction in performance through turbidity and saturation of active sites, which restricted penetration of photons and generation of ROS. The loading of catalysts is the key parameter to the maximum photocatalytic efficiency by employing minimum amount of catalyst use. The results confirmed that the moderate amount of catalyst give the balance of adsorption surface and light permeation.

Analysis of the Impact of agitation speed on degradation: **Figure 7(d)**, shows agitation rates effect (100-500 rpm) and degradation percentage increased from about 53% at 100 rpm to a maximum of approximately 60% at 200 rpm, followed by a gradual decrease at higher agitation speeds. Optimal degradation about 60% was observed when the agitation speed was 200 rpm. High speeds reduced degradation because there was no adequate contact time between catalyst surfaces and dye molecules. This finding justified that the mixing should be appropriate in order to achieve homogeneous dispersion of nanoparticles and the optimal contact to dye molecules. When agitation is excessive, efficiency is reducing, and therefore special attention should be paid to the regulation of the reaction parameters.

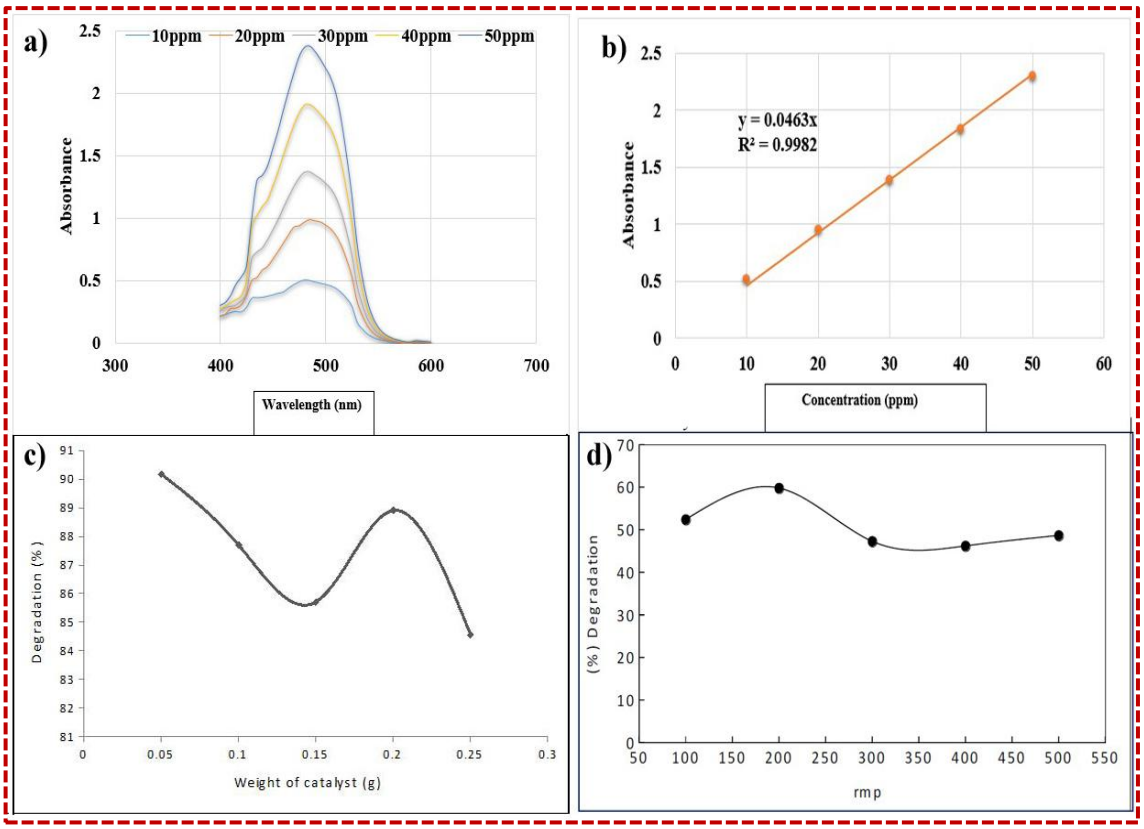

Figure 7: a) Visible region spectra of standard solutions of M.O with different concentrations, b) Calibration curve for dye Methylene Orange (M.O) showing excellent linearity c) Impact of catalyst dose on M.O degradation efficiency d) Impact of agitation on percentage degradation of M.B dye.

Temperature-Dependent Degradation: Photocatalytic studies were studied at 30, 40 and 50°C. The results in **Fig 8 (a)** showed that the rate of degradation was increased with increasing the temperature. At 30 °C, it was observed that approximately 10% of the dye was degraded after 10 minutes and it reached to 69 % after 70 minutes. At 40 °C, degradation efficiency reached 35% at 10 minutes and 83% at 60 minutes, whereas at 50 °C, it went up to 61% at 10 minutes and 92% at 60 minutes. This tendency demonstrated that the raise in temperature promotes the number of collisions between molecules and the generation of reactive oxygen species (ROS), which increases photocatalytic performance. Data of the temperature dependence can be also used to find the rate constants using pseudo-first-order kinetics, as shown in **Table 3.** The first-order behavior is confirmed by linear fits. The rate constants were observed to increase with temperature and attained 0.0185, 0.0279 and 0.0411 min^{-1} at 30, 40 and 50°C respectively, **Kinetic Studies of *Methylene Orange Degradation:*** The data of time-profiles were processed in terms of pseudo-first-order kinetics in **Figure 8(b)** and **Figure 8(c)** represent the kinetic plots at different temperatures and concentrations, respectively. **Table 4** represent the Rate constant determining for the degradation at different concentrations was used to find the rate constant for MO.

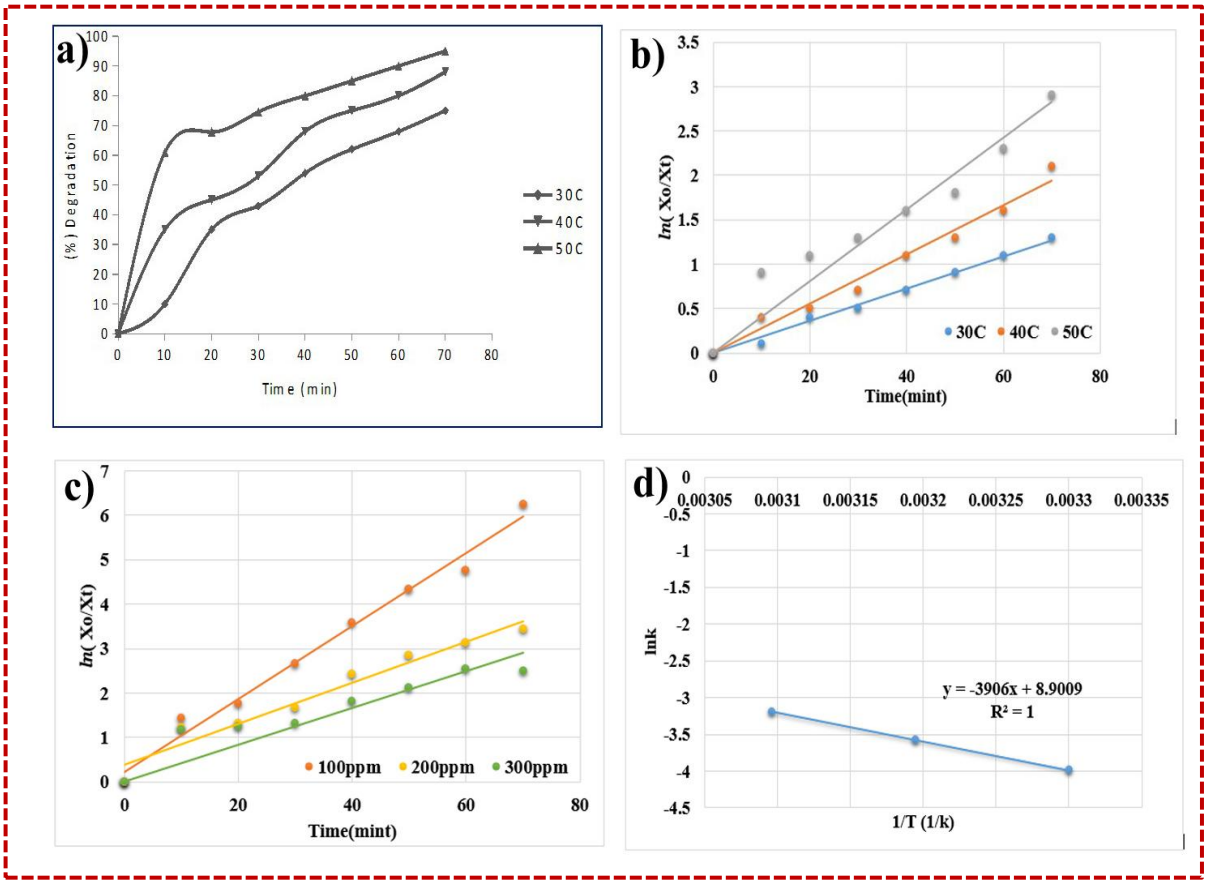

Figure 8: a) The influence of temperature on degradation efficiency of Methylene Orange by employing CuO catalyst, b) Fitted kinetic model to experimental data at various temperatures, **c)** Arrhenius Plot, d) Fitted kinetic model to experimental data at various concentration of M.O dye

Table 3. Rate constant calculated by applying on degradation data at various temperatures.

Temperature (°C)	K=min^{-1}

30	0.0185
40	0.0279
50	0.0411

Arrhenius analysis resulted in an activation energy of 32.6 kJ mol^{-1}, which demonstrated that moderate energy needs to generate ROS and transfer electrons and holes, which is good indicator of catalysis as shown in **Figure 8(d)**. The saturation of active sites and lower penetration of photons at higher loads of dyes leading to reduction of rate constant with increased in concentration of dye. The kinetic parameters highlighted that both dye concentration and temperature should be optimized to obtain an efficient photocatalytic treatment.

Table 4. Rate constant determining for the degradation at different concentrations was used to find the rate constant for MO.

Concentration(ppm)	Rate Constant (per min)
100	0.0823
200	0.0464
300	0.0416

Limitations and Future Perspectives

This study provides an initial assessment (preliminary investigation) of green-synthesized CuO nanoparticles and their application in the photocatalytic degradation of MB and MO dyes. The primary objective of this preliminary investigation to demonstrate the feasibility of green synthesis of CuO nanoparticles as an effective photocatalyst for dyes removal. A limitation of the current work is the absence of several advanced characterization techniques (TEM, EDX, BET, UV–DRS) that could offer deeper insight into the physicochemical properties of the nanoparticles were not performed in the current study due to instrumental and resource limitations. Therefore, the findings presented herein should be regarded as preliminary findings that establish a foundation for further investigation. Future research will involve comprehensive characterization (TEM, EDX, BET, UV–DRS) together with detailed studies of recyclability, and degradation mechanisms (TOC/COD analysis, intermediate identification, LC-MS/GC-MS analysis). Additional experiments will also be conducted to assess optimization, to further validate and expand this study different operational conditions will be investigated.

CONCLUSION

This study was able to provide a green, sustainable pathway towards the synthesis of copper oxide nanoparticles by employing *Centella asiatica* leaf extract, which acted as a natural stabilizing and reducing agent. SEM and TGA were used to characterize the synthesized nanoparticles that proved their crystalline structure, thermal stability, and heterogeneous nature. CuO nanoparticles were comprehensively analyzed on based of catalytic activity to two common dyes, which are methylene blue (MB) and methylene orange (MO) in aqueous medium. The process of degradation was pseudo-first-order was confirmed and activation energies (Ea) of CuO catalyst for degradation of M.B and M.O was calculated as 26.19 kJ/mol and 32.6 kJ/mol. The effect of experimental conditions including dye concentration, temperature, catalyst dosage, and agitation rate were examined extensively and it was found that optimized experimental conditions are critical to obtain the maximum degradation efficiency. In general, this study validates the prospects of green-synthesized CuO nanoparticles as economical, greener, and reusable photocatalysts in the treatment of wastewater

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