



WALLAGA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
GREEN SYNTHESIS AND CHARACTERIZATION OF $\text{CuO}/\text{Co}_3\text{O}_4$
NANOCOPOSITE USING *Ocimum lamiifolium* LEAF EXTRACT
FOR PHOTOCATALYTIC DEGRADATION OF METHYLENE BLUE

MSc THESIS

BY:

GODO TAKELE

December, 2025
Nekemte, Ethiopia



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**A thesis submitted to the collage of natural and computational sciences in
partial fulfillment of th requirements for the degree of masters of science in
inorganic chemistry**

MSc THESIS

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ADVISOR: RAJI FAYISA (PHD)

December 2025
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WALLAGA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

APPROVAL SHEET FOR SUBMITTING FINAL THESIS

As members of the Board of Examining of the Final MSc. thesis open defense, we certify that we have read and evaluated the thesis prepared by **GODO TAKELE** under the title “**Green Synthesis and Characterization of CuO/Co₃O₄ Nanocomposite using *Ocimum lamiifolium* leaf extract For photocatalytic Degradation of methylene blue dye**” and recommend that the thesis be accepted as fulfilling the thesis requirement for the Degree of Master of Science in **Inorganic Chemistry**.

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STATEMENT OF THE AUTHOR

I **Mr. Godo Takele**, hereby declare and affirm that the thesis entitled “**Green Synthesis and Characterization of CuO/Co₃O₄ Nanocomposite using *Ocimum lamiifolium* leaf extract For photocatalytic Degradation of methylene blue dye**” is my own work conducted under the supervision of Raji Feyisa (PhD). I have followed all the ethical principles of scholarship in the preparation, data collection, data analysis and completion of this thesis. All scholarly matter that is included in the thesis has been given recognition through citation. I have adequately cited and referenced all the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and I have not misrepresented, fabricated, or falsified any idea / data / fact / source in my submission. This thesis is submitted in partial fulfillment of the requirement for a degree from the Post Graduate Studies at Wallaga University. I further declare that this thesis has not been submitted to any other institution anywhere for the award of any academic degree, diploma or certificate.

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This is to certify that this thesis is entitled“ **Green Synthesis and Characterization of CuO/Co₃O₄ Nanocomposite using *Ocimum lamiifolium* leaf extract For photocatalytic Degradation of methylene blue dye**” is accepted in partial fulfillment of the requirements for the award of M.Sc. degree in Inorganic Chemistry by the School of Graduate Studies, Wallaga University through the College of natural and Computational Sciences, done by **Godo Takele** is genuine work carried out by him under my guidance. The matter embodied in this thesis work has not been submitted earlier for award of any degree. The assistance and help received during the course of this investigation have been duly acknowledged. Therefore, I recommend that it can be accepted as fulfilling the research thesis requirements.

Raji Feyisa (PhD)

Advisor

Signature

Date

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ABBREVIATIONS AND ACRONYMS

CB	Conduction Band
EDX	Energy Dispersive X-Ray Spectrometer
FT-IR	Fourier Transform Infrared
JCPDS	Joint Committee On Powder Diffraction Standards
MB	Methylene Blue
NCS	Nano composites
NPS	Nano composites
pHPZC	pH At Point Of Zero Charge
PXRD	Powder X-Ray Diffraction Analysis
ZC P	Point Of Zero Charge
SPR	Surface Plasmon Resonance
UV-VIS	Ultraviolet-Visible spetroscopy
VB	Valence Band

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ABSTRACT

The increase of environmental pollutions from industry due to organic dye effluents initiated the researcher to design a nanomaterial with a target of photocatalytic degradation capacity. The purpose of this study was to synthesize copper oxide nanoparticles (CuO NPs), cobalt oxide nanoparticles (Co₃O₄ NPs), and CuO/Co₃O₄ Nano composite system using Ocimum lamifolium plant leaf extract. A simple, eco-friendly, inexpensive, short-time consumer and biocompatibility approach was developed for the synthesis of CuO/Co₃O₄ NCs using O. lamiifolium leaf extract without employing any chemical stabilizer. The phytochemical screening analysis of the plant extract confirmed the presence of alkaloids, flavonoids, phenols, tannins and saponins. The synthesized crystalline nanoparticles were characterized by UV-Vis, FT-IR and XRD. UV-Vis absorbance peak for CuO NPs, Co₃O₄ NPs and CuO/Co₃O₄ were 310 nm, 394 nm and 341 nm respectively with an energy band gap 3.2 eV for CuO NPs, 3 eV for Co₃O₄ NPs, and 2.5 eV for CuO/Co₃O₄ NCs. The FT-IR result showed the presence of functional groups in the leaf extract and prepared nanoparticles. XRD analysis revealed that CuO NPs have a monoclinic crystal structure with an average crystallite size of 12.34 (nm,) whereas Co₃O₄ NPs have a cubic crystal structure with an average crystallite size of 16.58 (nm). The CuO/Co₃O₄ nano system exhibited an average crystal size of 19.19 (nm). Photocatalytic activity of CuO/Co₃O₄ NCs was performed under natural sunlight using methylene blue as organic dye pollutant. The dye was entirely decolorized and degraded by more than 96.134% after irradiation for 90min. Therefore, the present study provided that the CuO/Co₃O₄ nanocomposites may have good applications and high-efficiency of photocatalytic activity.

Keywords; *Ocimum lamiifolium, photocatalytic, Methylene blue ,CuO/Co₃O₄ Nanocomposite, Nanoparticle.*

1. INTRODUCTION

1.1. Back ground of the study

Nanotechnology is a technical field dealing with creation and usage of technologies on a scale that spans orders-of-magnitude usually from approximately 1 - 100 nm. There is also a study of a possibility of manipulation with a matter on an atomic and molecular scale, where quantum-mechanical phenomena differing diametrically from the macroscopic scale apply. Thanks to those phenomena new perspectives open in fields of magnetic recording media, computer technology, electronics, optics and other scientific fields. (Armakavicius *et al.*, 2024).

Evidently, increasing of the world's population is leading to unexpected urbanizations and industrializations in which it can cause environmental pollutions. Environmental and water contamination has been a major issue due to the discharge of organic dye pollutants into the water supply system from major industries such as paper, plastic, pharmaceutical, textiles, cosmetics, food, leather, medicine and many other industries (Kolya *et al.*.,2024). About 20% of dyes such as methylene blue, phenols and other phenolic dyes are released to the environment during manufacturing processes. The presence, accumulation and stability of these dyes in the environment and water body can cause severe effects on humans, animals, plants, the nature of water and inhibit the sunlight penetration and reduce the normal photosynthetic reaction since they are toxic, carcinogenic and mutagenic in nature (Larson *et al.*, 2020).

This societal issue was initiated the researcher to design a safe and cheap plant extract mediated nanomaterial with better potential photocatalytic activity. Organic dyes are stable organic pollutants that persist in the environment. Therefore, methods for their degradation have been increasingly explored and developed. Despite the number of successful systems employing various physicochemical and biological processes, economical removal of color from effluents remains a major problem (Piaskowski *et al.* , 2018). Therefore, it is necessary to develop better economically and environmentally friendly treatment technologies. Currently, photocatalytic degradation by nanoparticles is attracting significant attention. In photocatalytic degradation, the pollutants degraded under UV-Vis light irradiation in the presence of catalysts. Compared to the conventional

methods, this technique is inexpensive and does not form any polycyclic product (Mogashane *et al.*, 2025). Various approaches have been employed to remove MB dyes, including photocatalysis, biological treatment, ultrafiltration, and adsorption processes. Photo degradation is one of the most successful techniques because it decomposes harmful pollutants and converts them into harmless substances. As a result, heterogeneous photo catalysis is a promising area of study because it enables the complete mineralization of these environmentally harmful dyes (Akechatree *et al.*, 2025). Green chemistry is an approach to the design, manufacture and use of chemical products to intentionally reduce or eliminate chemical hazards. The goal of green chemistry is to create better, safer chemicals while choosing the safest, most efficient ways to synthesize them to reduce wastes and used as the photo catalytic activities (Osman *et al.*, 2024).

Green synthesis is an emerging area in the field of bio Nano technology and provides economic and environmental benefits as an alternative to chemical and physical methods. In this method, nontoxic safe reagents which are eco-friendly 'Green synthesis' are required to avoid the production of unwanted or harmful by-products through the build-up of reliable, sustainable, and eco-friendly synthesis procedures. The use of ideal solvent systems and natural resources (such as organic systems) is essential to achieve this goal. Green synthesis, a bottom up approach, is similar to chemical reduction where an expensive chemical reducing agent is replaced by extract of a natural product such as leaves of trees/crops or fruits for the synthesis of metal or metal oxide NPs (Thakur *et al.*, 2025).

Ocimum lamiifolium plant belongs to the subgenus *Nautochilus*, family *Lamiaceae*, and subfamily *Nepetoideae*. The genus *Ocimum* comprises more than 150 species that are distributed from tropical to subtropical regions (Shikha *et al.*, 2023). The plant is an indigenous plant to Ethiopia and has different names in the vernacular languages of Ethiopia, like 'damakase' by Amharic, 'Anchabi/Qoricha michi' by Afan Oromo, Akawayya by Gumzegna, and 'Guluuwa/Desha dunkiya' by Dawuro (Dubale *et al.*, 2023).

Synthesis of CuO/Co₃O₄ Coaxial Heterostructures for efficient and Recycling Photodegradation (Chen *et al.*, 2015). Green synthesis of CuO NPs, Co₃O₄ NPs, and CuO/Co₃O₄ Nano system using an extract from *Moringa stenopetala* plant leaf extracts leaves to evaluate their antioxidant and against selected bacterial strains (Tefera *et al.*, 2024). However, improved catalytic efficiencies and antibacterial activity still need further

exploration of green synthesis CuO-based Nano composites. On the other hand, there is no reported study on the green synthesis of CuO/Co₃O₄ Nano composites using *Ocimum lamiifolium* leaf extract. Thus, in view of this respect, the current work is focused on the green synthesis of CuO/Co₃O₄ NCs using *Ocimum lamiifolium* leaf extract for photocatalytic degradation of methylene blue. The study were investigates the impact of reaction parameters on the synthesis and photocatalytic activity of these nanocomposites. The CuO/Co₃O₄ NCs were analyzed comprehensively by several methods, including UV–VIS, FT-IR, and XRD

1.2. Statement of the Problem

The release of coloured dyes like methylene blue (MB) into the environment has been of great concern due to the properties and effects of dye contaminated water on the environment (Bopape *et al.* ., 2024). Dye contaminated wastewater disposal is of prime concern because it is toxic to humans and aquatic life. These dyes are not biodegradable and cause water pollution and serious long-term effects on the environment. Therefore, to minimize the health effects of these pollutants, treatment methods need to be studied. Methods of removal of these dyes such as adsorption by activated charcoal are not effective; since they result in large amounts of sludge which can cause pollution problems again. Therefore, photocatalysis has been proven to be a more efficient method for the degradation of MB (Khan *et al.* ., 2022)

The green synthesis of CuO/Co₃O₄ Nano composite by the use of *Ocimum lamiifolium* leaf extract and Application of photocatalytic activities has not been reported. So this study is intended to explore green synthesis method of CuO/Co₃O₄ Nano composite from *Ocimum lamiifolium* leaf extract and to examine photocatalytic efficiency of synthesized CuO/Co₃O₄ Nano composite from leaf extract. The *Ocimum lamiifolium* leave extract act as reducing and capping agent for the synthesis of CuO, Co₃O₄ NPs and CuO/Co₃O₄ NCs and What is the efficiency of photocatalytic degradation activity of the synthesized CuO/Co₃O₄ nanocomposites?

1.3. Objectives

1.3.1. General objective

- The main objective of this work is green synthesis and characterization of CuO/Co₃O₄ nanocomposite using *ocimum lamiifolium* leaf extract for photocatalytic degradation of methylene blue dye.

1.3.2. Specific objectives

- To identify and screen phytochemical constituents of *Ocimum lamiifolium* leaf extract.
- To synthesis of CuO NPs, Co₃O₄ NPs and CuO/Co₃O₄ Nano composite by using green approach.
- To characterize green synthesis of the CuO NPs, Co₃O₄ NPs and CuO/Co₃O₄ nano composites using Ultraviolet Visible Spectroscopy (UV vis), Fourier Transform Infrared Spectroscopy (FTIR) and X-ray Diffraction (X-RD).
- To evaluate the photocatalytic performance of the nanocomposite for degradation of methylene blue dye

1.4. Significance of the Study

The green synthesis of nanoparticles and Nano composites using plant extract is an active area of current research, attracting the interest of many researchers because of their wide applications. Nowadays due to increase of water pollution synthesis of nanoparticle and Nano composites are highly important. Therefore, the finding of this study was used: To enhance the knowledge about CuO NPs, Co₃O₄ NPs and CuO/Co₃O₄ NCs regarding to the photo catalytic applications and the set foundation for further investigation of applications of CuO, Co₃O₄ NPs and CuO/Co₃O₄ NCs.

2. LITRATURE REVIEW

2.1. Environmental Pollutions Due to Dye Effluents and Human Health Issue

We are in the era of urbanization and industrialization, which requires different domains of electronics, energy storage devices, ecological remediation, microbial inhibition, medical implants and optical appliances (Bradú *et al.*, 2023). About 10,000 different commercial organic dyes and pigments exist and more than 7×10^5 tons are produced per year over the worldwide and have been used in many industries such as textiles, printing, leather, pulp, food and plastics, etc. Approximately, 10-15% of these dyes are released through effluents after dying processes and can cause the environmental pollution. As these compounds are toxic and carcinogenic in nature, their impact on the environment and human health is a major concern. Furthermore, these dyes impart color to aqueous body by blocking the penetration of sunlight and dissolution of oxygen (Kolya *et al.*, 2024).

Nowaday, there is a growing need to develop the ecofriendly techniques for nanoparticle synthesis in order to increase its application in the medical and environmental platforms which can avoid the use of hazardous chemicals and solvents (Jain *et al.*, 2024). Synthesis of nanomaterials through different physical and chemical routes possess an inherent damage to the environment, economy, need for high temperature and pressure, expensive equipment, toxic reagents, longer reaction time, and needs manual effort. In contrary, biological entities (i.e. bacteria, fungi, and plants) can be used as the bio factories for NP synthesis since it is a simple and ecofriendly method (Jain *et al.*, 2024).

2.2. Nanomaterials, Nanoscience and Nanotechnology

Nanomaterial is a substance having a nano scale dimension of 1-100 nm. The unit of nanometer derives its prefix nano from a Greek word meaning “dwarf” or “extremely small.” One nanometer span 3-5 atoms lined up in a row. By comparison, the diameter of a human hair is about 5 orders of magnitude larger than a nanoscale particle. Nanomaterial exhibits unique physical and chemical (optical, magnetic, electrical etc) properties absent in both the molecular and bulk solid state (Al-Harbi *et al.*, 2025). Nanomaterials can be metals, ceramics, polymeric, or composite materials. Their unique properties lead it to have a great application potential in the field of nano technology,

electronics, medicine, and other fields by displaying different physical and chemical characteristics from normal chemicals (i.e., silver nano, carbon nanotube, fullerene, photocatalyst, carbon nano, silica). Many components of electronic and optical devices used for information processing, storage, and display are being improved through the development of new solid-state materials nanotechnology (Wang *et al.*, 2024). Nanomaterials can be nanoscale in one dimension (eg. Surface films), two dimensions(eg.strands or fibers), or three dimensions (eg. particles). They can exist in single, fused, aggregated or agglomerated forms with spherical, tubular, and irregular shapes (Ulusoy *et al.*, 2023).

Nanotechnology is the collection of procedures for manipulating matter in scale in order to build nanosized entities for useful purposes. Thus, nanomaterials are cornerstones of nanoscience and nanotechnology which taken to be as solid material and exhibits novel properties related to its scale. Nanotechnology is a promising science with wide applications from cosmetics, food products, clothing, and household appliances to fuel catalyst, disease treatment, and renewable energies; And is also being applied to a variety of industrial and purification processes including construction materials, nanomachining of nanowires, nanorods, graphene, water filtration, and wastewater treatment, energy storage, automotive parts, thin-film electronics, coatings, and so forth (Elgarahy *et al.*, 2024).

2.3. Methods for Synthesis of Binary Nanocomposite

There are three basic fabrication techniques of nanoscale entities, namely physical, chemical and biological synthesis approaches. Physical synthesis process basically depends upon the instruments used in the experiment. Electron beam lithography, arc discharge and ball milling are among methods used for synthesis of nanomaterials (Krishnia *et al.*, 2022). Chemical method of synthesizing NPs depends on chemicals, reducing and capping agents along with an optimum condition of temperature and pressure. Electrochemical, microemulsion, ozonation etc. are some of chemical synthesizing techniques. The biological approach for NPs synthesis is ecological agreeable and is called “Green synthesis” due to its non-toxic, save reagents, not perilous to any living beings. Fig. 1 shows that different synthesizing methods of nanoparticles (Vijayaram *et al.*, 2024).

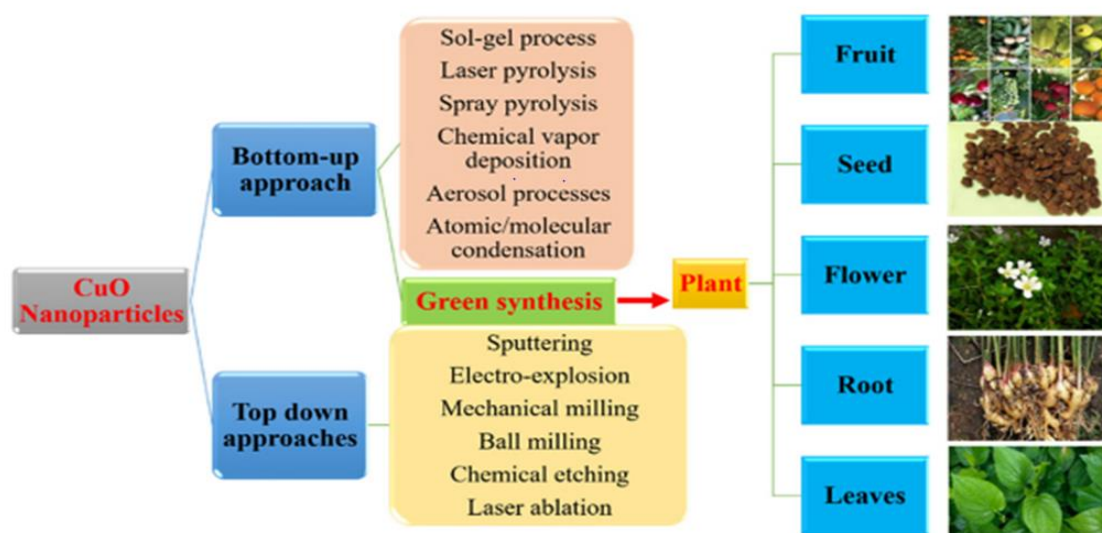


Figure 1. Different Methods for Synthesizing of Nanoparticles.

The synthesis approaches are also classified into physical, chemical and biological synthesis depending on the processes or materials involved in the production process.

2.3.1. Physical Method

In physical approaches, the bulk or micro-sized precursors are downsized into ions or atoms via evaporation, laser ablation, molecular beam, and sputtering processes. Physical synthesis approaches mostly yield monodispersed, pure metal oxide nanoparticles, and their toxicity towards living organisms is due to potential disintegration into ionic states in biological fluids (Andra *et al.*, 2024). In addition, the separation of nanoparticles from the substrate requires the use of toxic solvents and chemicals as a stabilizing agent to avoid agglomeration of nanoparticles (Abbas *et al.*, 2024). It is noteworthy that these complex chemical-stabilizing agents are highly toxic to living cells (Sonawane *et al.*, 2025).

In the physical method, physical forces are involved in the attraction of nanoscale particles and formation of large, stable, well-defined nanostructures (Agarwal *et al.*, 2024). It also includes basic techniques like vapour condensation, amorphous crystallization, physical fragmentation and many others. Using physical approaches, we can get nanoparticles with high purity and definite shape. However, these processes are usually involves the use of highly sophisticated instruments, chemicals and radiated heating as well as high power consumption, high temperature and pressure which lead to high operating cost (Rezvani 2025) large space area for setting up of machines.

2.3.2. Chemical Method

To synthesize MNPs and MONPs, researchers used a strong base (reducing agent) in metal ion reduction from salt solutions, followed by the addition of a capping agent or a stabilizer (stabilizing agent) (Naseem *et al.*, 2024). To dissolve the stabilizers, they used solvents and the reagents that act as reducing agents, which are toxic substances and have counteractive and harmful effects if the rest of these materials are left in the rear part of the nanosystem, as the bottom-up path to synthesize the nanoparticles often needs the offensive chemical reduction agents and a capping agent and may also involve a volatile organic solvent. Although these procedures may effectively produce pure products, the manufacturing cost is high, both materially and environmentally (El Shafey, 2020).

Most chemical methods frequently exploit hazardous reducing agents such as sodium borohydride, ethylene glycol, hydrazine, and sodium citrate, but they result in poor control over the particle size and size distribution; thus, additional capping or stabilizing agents such as ascorbic acid, polymers (e.g. polyethylene glycol, poly(vinyl alcohol), poly(vinyl pyrrolidone)), ligands (e.g. octadecylamine, pyridine), dendrimers, surfactants (e.g. cetyl trimethyl ammonium bromide, sodium dodecyl sulphate), phospholipids and gemini surfactants are needed to ensure steric stabilization to prevent the nanoparticles from agglomeration (Tukova *et al.*, 2024).

A high thermal decomposition treatment is then introduced to eliminate the reducing and stabilizing agents adsorbed on the nanoparticle surface, which may block the active sites of particles, consequently resulting in a decreased surface area and deteriorated reactivity of the products (Zeng *et al.*, 2024). In addition, thermal annealing is necessary to obtain good crystalline samples. The high cost and hazardous properties of this synthetic approach may hinder large-scale application. Moreover, this procedure produces a low yield of the products. To eliminate all different drawbacks of physical and chemical methods, scientists and researchers are focused on alternative process of metals and their oxides nanoparticle synthesis (Kiarashi *et al.*, 2024).

2.3.3. Green Method

In materials science, “green” synthesis has gained extensive attention as a reliable, sustainable, and eco-friendly protocol for synthesizing a wide range of materials/nanomaterials including metal/metal oxides nanomaterials, hybrid materials, and bio inspired

materials. As such, green synthesis is regarded as an important tool to reduce the destructive effects associated with the traditional methods of synthesis for nanoparticles commonly utilized in laboratory and industry (Singh *et al.*, 2024). This approach is an environment-friendly, cost-effective, biocompatible, safe, green approach (Salam *et al.*, 2024).

Green synthesis approaches are gaining significance as promising routes for the sustainable preparation of nanoparticles, offering reduced toxicity towards living organisms and the environment. Nanomaterials produced by green synthesis approaches can offer additional benefits, including reduced energy inputs and lower production costs than traditional synthesis, which promised well for commercial-scale production. The use of plants or plant extracts for metal and metal-based hybrid nanoparticle synthesis represents a novel green synthesis approach that has attracted significant research interest (Jeevanandam *et al.*, 2022). With the purpose of developing a safer approach towards nanomaterials production, researchers have been emphasizing the importance of green synthesis methods as opposed to other chemical and physical routes. Green synthesis methods are often favoured as it is facile, cost effective, energy saving and utilizes sustainable resources. Therefore, the methods can be easily scaled up with minimum toxic by-products released into our ecosystem (Bordbar *et al.*, 2023).

a) Use of plants or their extracts for the green synthesis of NPs

In the “one-pot” synthesis method, reduction, as well as stabilization of metallic NPs, are achieved through the utilization of plants or plant extracts. Biomolecules derived from plants, such as carbohydrates, proteins, and coenzymes, possess the capability to reduce metal salts into NPs. For instance, aloe vera is employed simultaneously as a reducing and capping moiety in the synthesis of silver and gold NPs. Additionally, tulsi leaves (*Osimum sanctum*) have been utilized to synthesize spherical and rod-shaped silver NPs (Al-Zahrani *et al.*, 2024). Figure. 2 represents the stepwise procedure and basic mechanism followed for the synthesis of AgNPs via the green synthesis. In recent years, this approach has attracted researchers across the world due to the replacement of harmful and costly chemicals by eco-friendly and cost effective green reagents (Castiello *et al.*, 2023).

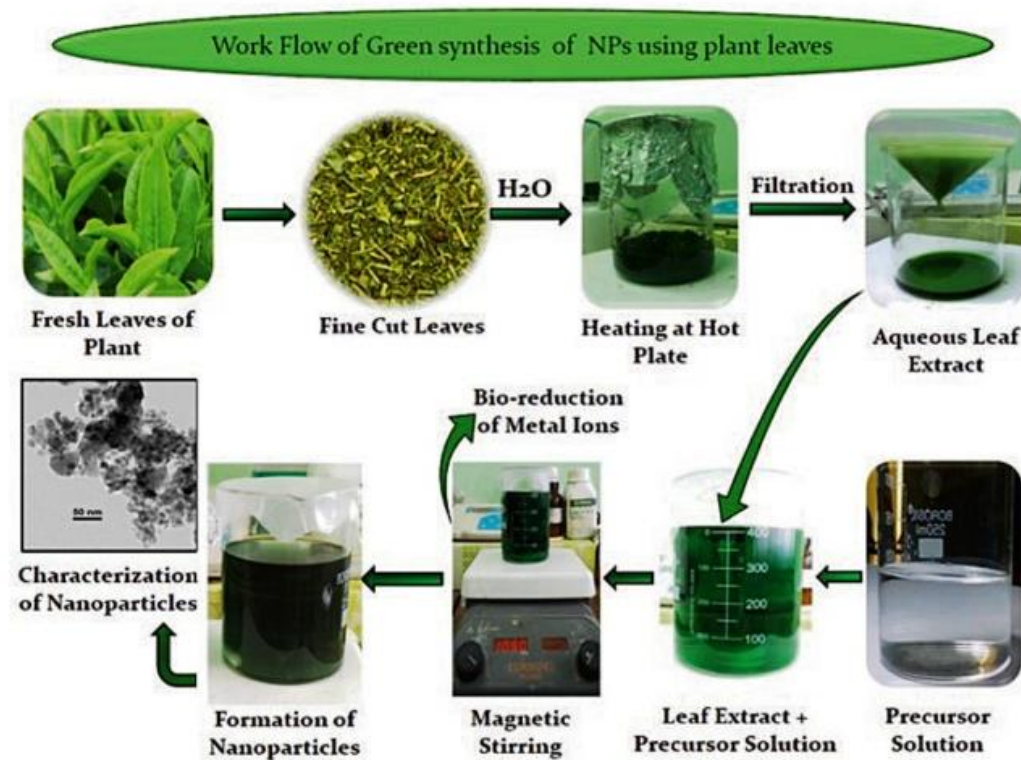


Figure 2. Pictorial representation for green synthesis of MNPs using plant extracts.
Reproduced with permission from (Jadoun *et al.*, 2021)

b) Use of bacteria for the green synthesis of NPs

Microbes, like bacteria, are also used for the green synthesis of NPs. Cadmium sulfide (CdS) NPs synthesized using *Escherichia coli*, exhibited more potent anticancer activity than the standard anti-cancerous drug, 5-Aminolevulinic Acid (5-ALA). Silver and selenium NPs were produced using *Lactobacillus casei*, and these demonstrated strong antibacterial and anti-cancer effects in colon cancer (Haji Mehdi Nouri *et al.*, 2024). *Bacillus cereus* was utilized in the production of silver and zinc oxide NPs. The bacterium *Bacillus subtilis* was also utilized for the synthesis of gold NPs.

2.4. Application Of Green Synthesis Of Metal Nanoparticles

Researchers affirmed that biologically synthesized nanoparticles are more pharmacological active compared to other physicochemical methods. Plant extract synthesized metallic nanoparticles are stable and monodispersed easily by controlling different influencing factors such as pH, temperature, retention time, and mixing ratio. Green metal nanoparticles synthesized by different plants such as neem leaves (*Azadirachta indica*), tulsi leaves (*Ocimum tenuiflorum*), curry leaves (*Murraya koenigii*),

guava leaves (*Psidium guajava*), and mango leaves (*Mangifera indica*) (Guleria *et al.*, 2022).. The metallic nanoparticles green synthesized using diverse medicinal plants have shown the most important therapeutic properties, namely antimicrobial activity, insecticidal activity, antioxidant activity, wound healing properties, antidiabetic activity, immunomodulatory activity, hepatoprotective activity, and anticancer activity (Figure 3). The medicinal plant-based synthesized metallic nanoparticles have a huge beneficiary effect in the sector of biomedicine. The major significant concept of using green nanotechnology in agriculture reduced harmful environmental effects and the high expenditure of fertilizers, while green nanoparticles (GNPs) synthesized from dissimilar plants reduced the harmful emission of carbon dioxide, nitrous oxide, and methane. Also, green nanoparticles are used to increase productivity in agriculture and lower health risks concerned agricultural farmers. Naturally, plants contain numerous phytochemical components.

These factors are eco-friendly and inexpensive. Green synthesized nanoparticles are exposed to the significant importance of heavy metal detoxification from the environment. In view of the number of heavy metals polluting soil and water, green nanoparticles are helpful to reduce metal toxicity in the environment (Singh *et al.*, 2018). As the different parts of plants roots, stem, leaf, seed, and fruit contain many phytochemical substances, the green synthesis metallic nanoparticles approach is cost-effective, non-toxic, and eco-friendly and is more efficient compared to other biological methods. For the synthesis of green nanoparticles, it is important for selected plant parts to be washed with tap or distilled water, after squeezing, filtering, and adding particular salt solutions. The color modification of the solution confirms the synthesized nanoparticles. Phytochemical components (phenolic acids: ellagic acid, caffeic acid, protocatechuic acid, and gallic acid) play an important role in the synthesis of metal nanoparticles. The phytochemical factors are reducing and stabilizing agents of synthesized metal nanoparticles (Ovais *et al.*, 2018).

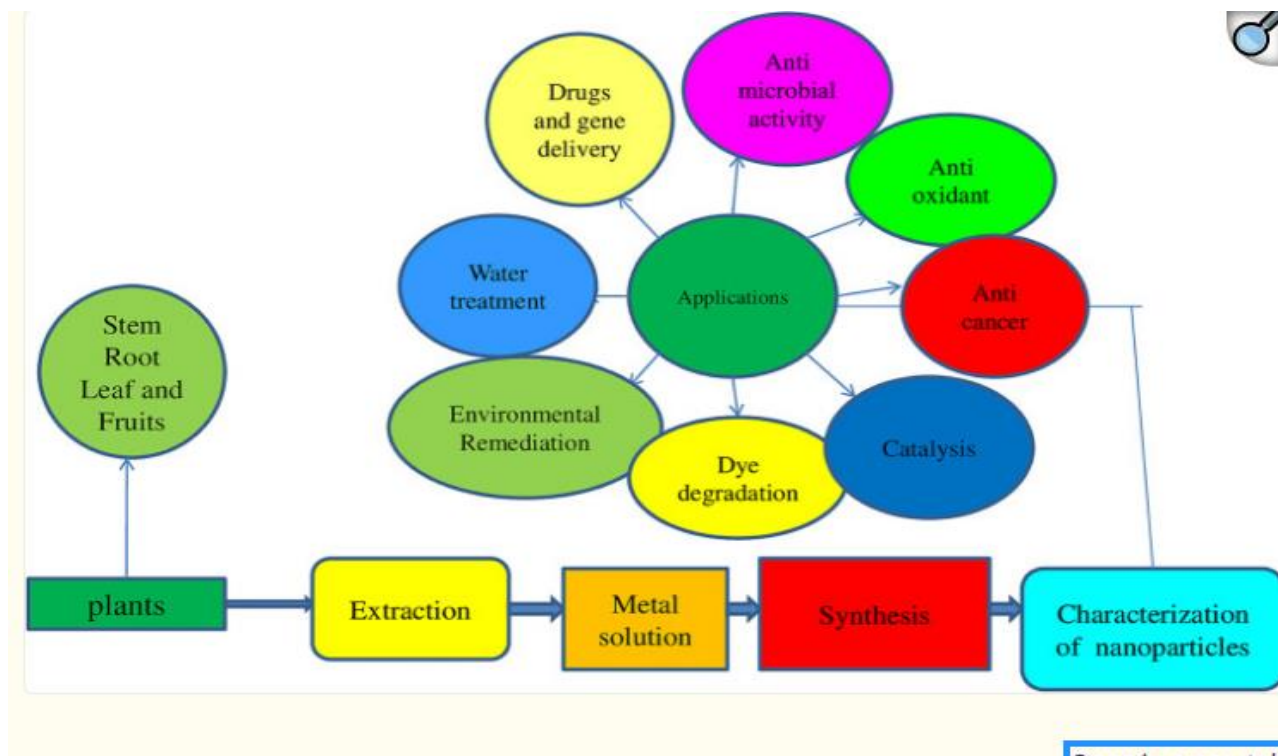


Figure 3. Green synthesis of metal and metal oxide nanoparticles and their applications

2.5. Characterizations of Green synthesis of Nanoparticles and Nano composite

The great advances made in nanosciences and nanotechnology would not have occurred without the ability to characterize the nanoscale structural, chemical, and physical properties of materials. Moreover, the direct observation of nanostructure allows meaningful relationships between processing and properties to be made (Habeb *et al.*, 2024).

2.5.1. Ultraviolet-Visible (UV–Vis) Spectroscopy.

UV–Vis spectroscopy is the valuable technique commonly used to identify the structural characterization, formation and stability of metal nanoparticles in aqueous solution by analysing the unique optical properties and optical band gap which depends on the size and the shape of the nanoparticles between 200 nm to 800 nm. It is well recognized that the optical absorption peak of metal nanoparticles is dominated by surface plasmon resonances (SPRs) that shift to longer wavelengths with increasing particle size due to the capping agent. The SPR mainly depended upon the size and shape of nanoparticles (Abbas *et al.*, 2024). The metal ion reduction can be confirmed by the apparent change in

the color of the reaction mixture as characterized by UV-vis spectrum. Indeed, no color transformation can be noticed in the absence of plant extract, under a similar set of situations. The formation of NPs was further confirmed by UV-vis spectral study, which is a reliable technique to monitor the progress of the reaction during the reduction of metal ions. The UV-vis spectrum of green synthesized NPs using plant leaf extract can show the significant changes in the absorbance maxima due to surface plasmon resonance demonstrating the formation of NPs. The band gap energy of photocatalysts can be determined based on its adsorption edge wavelength according to equation $E_g = 1240/\lambda$ (Ahmed *et al.*, 2024).

2.5.2. Fourier Transformed Infrared Spectroscopy (FT-IR).

FT-IR spectroscopy is used to identify the possible functional groups of the active components present in the extracts or on the surface of NPs that are responsible for reducing, capping and stabilizing of being synthesized nanoparticles. The functional groups are identified in the ranges of 4000-400 cm^{-1} . The FT-IR peaks attributed to stretching and bending vibrations is identified and assigned the different functional groups present in the leaf extract and as well as in the nanoparticles (Pasiieczna-Patkowska *et al.*, 2024)]. The FT-IR spectrum of plant extract exhibits several absorption peaks at different locations, and which are associated with the several oxygen-comprising functional groups. After the reaction, a majority of the peaks exist in the FT-IR spectrum of NPs, but they decreased in intensity and also showed with few marginal shifts into lower wavenumber. Consequently, the occurrence of these peaks evidently indicates the dual role of the plant extract, both as a green reducing agent and as a stabilizing agent (Villagrán *et al.*, 2024)].

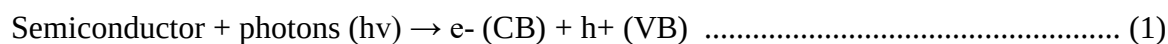
2.4.3. Powder X-ray Diffraction (XRD) Analysis.

The XRD spectra are used to confirm the crystalline nature, the structure, phase purity and composition of synthesized nanoparticles. The X-ray diffraction pattern of nanoparticles can be confirmed by the characteristic peak observed in XRD image. The data are collected in the 2θ range. The average crystalline size of the NPs can be calculated using Debye-Scherrer's equation (Gakuru *et al.*, 2024).

2.6. Photocatalytic Activity

The photocatalytic oxidation of organic pollutants is undergone using semiconductor photocatalysts that can absorb light energy (Ahmadi *et al.*, 2025). Only photons with energies greater than the band gap energy can result in the excitation of valence band (VB) electrons which then promote the possible reactions with organic pollutants. The absorption of photons with energy lower than the band-gap energy or longer wavelengths usually causes energy dissipation in the form of heat. The illumination of the photocatalyst with sufficient energy leads to the formation of a positive hole (h^+) in the valence band and an electron (e^-) in the conduction band (CB). The positive hole oxidizes either the pollutant directly or water to produce hydroxyl radical $\bullet OH$, whereas the electron in the conduction band reduces the oxygen adsorbed on the photocatalyst (Tuama *et al.*, 2024).

When the semiconductor is illuminated by photon energy equal to or greater than the band-gap energy (E_g), it excites electrons (e^-) from the VB to CB. Simultaneously, it causes the formation of a positive charge called a hole (h^+) in the valence band and electron at the conduction band (Tuama *et al.*, 2024). The photo generated positive holes react with water to produce hydroxyl radicals ($\bullet OH$) while the photo generated electrons react with oxygen and produce superoxide radicals ($O_2^{\bullet -}$). Both of these primary products (specifically $\bullet OH$ radicals) are strong oxidizing species that attack organic pollutants such as MB and decomposes them into CO_2 and H_2O (González *et al.*, 2025). (Figure 4) and their reaction is as shown as equation below.



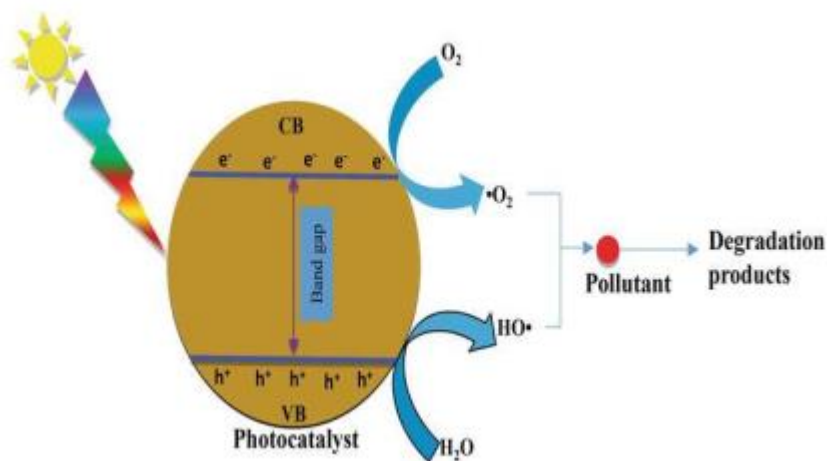


Figure 4. Proposed mechanism of photocatalytic degradation

2.7. Classification of dyes

Dyes come in two main categories: (I) natural dyes and (II) synthetic dyes. Natural dyes are typically derived from herbal plant sources (root, stem, leaves, bark, and flowers), as well as from minerals and animal sources (Alegbe *et al.*, 2024).. In addition, synthetic dyes can be divided into three groups: anionic dyes (which are water-soluble, and include acid, direct, and reactive dyes), cationic dyes (basic dyes), and non-ionic dyes (dispersing, pigment, and solvent dyes)(Millbern *et al.*, 2024). Most of cationic dyes are hazardous, including both humans and aquatic ecosystems, making them more poisonous than anionic dyes.

Dyes can be classified based on their various applications, which include textiles, food, cosmetics, and more. These classifications help organize dyes according to their intended use and suitability. Classifying dyes based on their application helps industries choose the most suitable dye(s) for specific purposes while ensuring safety, durability, and regulatory compliance. Dyes can also be classified based on color properties, chemical structure, and the way they interact with light. This classification explains the underlying chemistry of dyes and their suitability for various applications. The chemical structures of

some common dyes are presented in Figure 2.

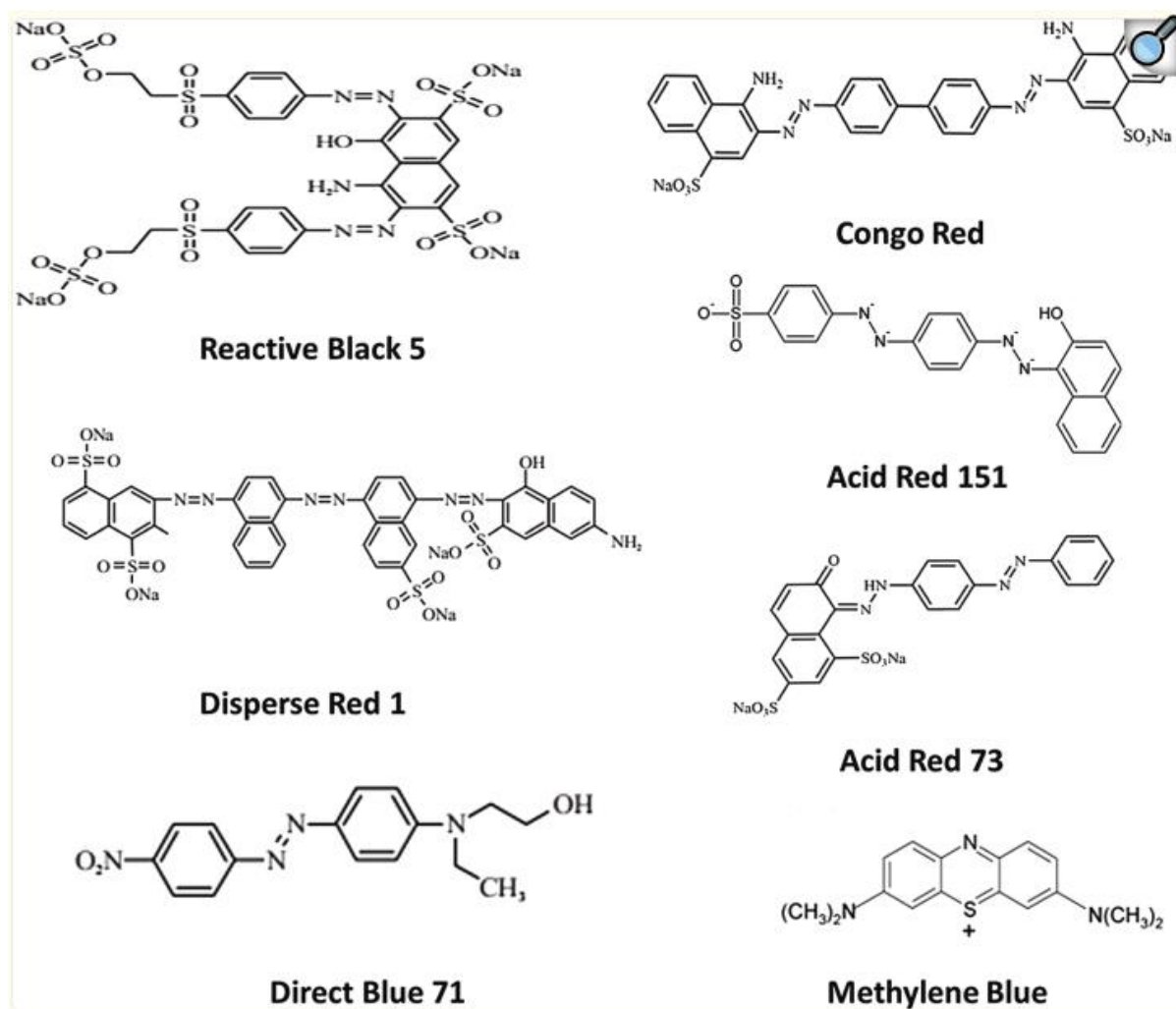


Figure 5 . Chemical structures of some common dyes

2.8. Removal of Dyes from Wastewater

The number of articles on various existing physicochemical and biological treatment techniques is shown in which confirms that among these technologies, adsorption is considered to be one of the most important and useful decontamination processes. It is considered to be a fast, low cost, simple, sludge-free process, having high efficiency and/or selectivity, mechanical stability, and recycling facilities. The adsorption process is widely used for the remediation of different pollutants from wastewater, including heavy metals, arsenic, and dyes(Raji *et al.*, 2023). Additionally, a pie chart displaying the percentage of literature available on dye removal using various adsorption techniques is shown in Fig. 3b. Considering this, the present study aims to review dye removal from polluted water *via* the adsorption process using various types of adsorbents. Specifically,

several adsorbents, including activated carbon, metal oxide-based, carbon-based, bio-adsorbent, metal–organic framework (MOF), and polymer-based materials, are widely applied for the adsorption of dye from polluted water. These adsorbents possess the advantages of easy fabrication, high effective surface area, multi-functionalities, high surface volume ratio, high reactivity, large number of active sites, reusability, low cost, and high efficiency to treat recalcitrant compounds.

2.9. Factors Affecting The Photo Catalytic Degradation Of Dyes.

a) pH Effect

Due to its numerous many responsibilities, including electrostatic interactions between the photo catalyst external surfaces, solvent particles molecules, adsorbent, and charged radicals created during the reaction procedure, pH impacts on the dye photo degradation method are particularly important. The charge on the catalyst surface and the charge on the dye molecules typically cause pH to have an impact on photo catalysis, increasing or decreasing the activity. The photo degradation efficiency was therefore 96.26% at pH 2, whereas the MB dye efficiency enhanced to 98.71% at pH 4 (Nagamani 2024). However, the photo degradation activity decreased as the pH level rose higher. The interference between the negatively charged dyes and the positively charged catalyst surfaces (NPs) in the acidic solution ($\text{pH} \frac{1}{4} 3$), increases removal efficiency. Increased dye adsorption occurred as a result of a cumulative increasing electrostatic interface interaction between the positively charged dye and the negatively charged catalyst when the dye solution became more basic ($\text{pH} > 7$).

b) Catalyst Load

According to research, the amount of catalyst loading significantly affects photo catalytic activity. When the catalyst (CuO NPs) concentration was increased from 2 to 8 mg/mL, MB degradation rose from 40 to 96% (Jeevarathinam *et al.*, 2024). The photo degradation activity did not increase further when the catalyst concentration was increased from 8 to 12 mg/mL (Li *et al.*, 2024). The particles are small and widely scattered at lower concentrations. This increases the active sites and surface area, which boosts the NPs' ability to photo, degrade dye (Thakur *et al.*, 2024). The catalyst accumulated and dissolved, which caused a rapid decline in photo degradation effectiveness. Additionally, at larger NP catalyst loading, the suspension becomes opaque and more turbid, which

causes light scattering. As a result, less radiation is able to pass through the material (reaction mixture) (Dehghan *et al.*, 2024).

c) Temperature, Time And Morphology

Temperature, duration, and shape all have a significant impact on photocatalytic performance are used green-synthesized CuO NPs in the temperature range of 25-40 °C to demonstrate that temperature affects the rate of pollutant breakdown. According to the degradation efficacy values, a minor increase in reaction rate is brought on by a rise in temperature. The moderate increase in photocatalytic degradation caused by raising the temperature may be caused by an increase in molecular collision frequency. Higher temperatures may also cause the contaminated molecules to turn into disabled from the catalyst surface, reducing the rate of reaction. The removal of oxygen from the reaction mixture, alternately, is caused by intense temperatures and is essential for the oxidation of contaminants (Huang *et al.*, 2024).

2.10. Traditional Medicinal Uses of *Ocimum lamiifolium* leaf (Ancabbii)

Traditional medicinal plants are an integral part of primary healthcare and have been used extensively as traditional treatments for both humans and animals in developing countries (Izah *et al.*, 2024). As the country is rich in plant biodiversity, more than 1000 species of medicinal plants have been identified, including *Ocimum lamiifolium* (Megersa *et al.*, 2024). Thus, the use of traditional medicine for healthcare purposes is an integral part of the culture, belief structure, and lifestyle of Ethiopian people (Agize *et al.*, 2022). *Ocimum lamiifolium* belongs to the subgenus *Nautochilus*, family *Lamiaceae*, and subfamily *Nepetoideae*. The genus *Ocimum* comprises more than 150 species that are distributed from tropical to subtropical regions.

The plant is an indigenous plant to Ethiopia and has different names in the vernacular languages of Ethiopia, like ‘damakase’ by Amharic, ‘Anchabi/Qoricha michi’ by Afaan Oromo, Akawayya by Gumzegna, and ‘Guluuwa/Desha-dunkiya’ by Dawuro (Derso *et al.*, 2024). In Ethiopia, the traditional use of medicinal herbs for the treatment and prevention of ailments has long been widespread (Alemu *et al.*, 2024). As a result, damakase (*Ocimum lamiifolium*) has been one of the most important and widely used raw forms for treating different diseases in traditional medicine by Ethiopians for a long period.

Ocimum lamiifolium is commonly used to treat gastrointestinal disorders (diarrhea, stomach cramps, and diarrhea), inflammation, fever, malaria, respiratory problems (coughs, colds, and bronchitis), skin infections (wounds, burns, and fungal infections), and pain and inflammation (headaches, burns, and joint pain) (Megersa *et al.*, 2024)).



Figure 6. *Ocimum lamiifolium* plant leaf

3. MATERIAL AND METHODS

3.1. Chemicals and reagents

All the chemicals were used such as, copper sulphate penta hydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, 99.8%) Sodium hydroxide (NaOH Sigma Aldrich 99% purity), Cobalt nitrate hexhydrate ($\text{Co NO}_3 \cdot 6\text{H}_2\text{O}$ 99.9%), Ferric chloride sigma Aldrich 99% purity, chloroform, Hydrochloric acid (HCl), Sigma Aldrich 98% purity), Ethanol ($\text{C}_2 \text{H}_5 \text{OH}$ 99.8%, Ethiopia), Distilled water. All Chemicals and reagents were purchased from which the chemicals or reagents there.

3.2. Instruments and Equipments

Instruments were used for characterizing the synthesized Nano particle Nano composite (NCs) including UV-Vis spectroscopy, which helped us to study the optical properties of the nanoparticles and Nano composite, FT-IR), for analysis of the vibrational modes of atoms in the molecules, XRD, to characterize the nature of crystal structure of nanoparticles and the apparatus were used like Oven, Mortar and Pestle, Digital balance, Hot Plate and Magnetic bar, Watch, Centrifuge, Filter paper, Beakers, Test tubes, Droppers, Graduated cylinders, Glass rode, Rack, Cuvettes, Refrigerator, Erlenmeyer flask , PH meter.

3.4. Sample Collection and Preparation of *Ocimum lamiifolium* leaf Extract

Ocimum lamiifolium leaf samples were collected from Wallaga University, around Botanic garden 331 Km away from Addis Ababa and the scientific name of the *Ocimum lamiifolium* was authenticated in wallaga university biology department by Dr Tashome Gemechu. Sample collection and preparation of *Ocimum lamiifolium* leaves extract were carried out according to the procedure written on the reported literatures (Mengistu *et al.*, 2025). *Ocimum lamiifolium* leaf were collected and the collected fresh leaves were washed thoroughly with tap water to remove any dust particles. The washed leaves were air-dried in dark place and about 10 gm. of the grinded leaves along with 100 mL of distilled water was heated in a hot plate at 60°C for 30 min. After 30 min, it was filtered

using Whatmann No 1 filter paper having pore size and kept in refrigerator. Then, the prepared extract was used for the synthesis of CuO NPs, Co₃O₄ and CuO/Co₃O₄ NCs.

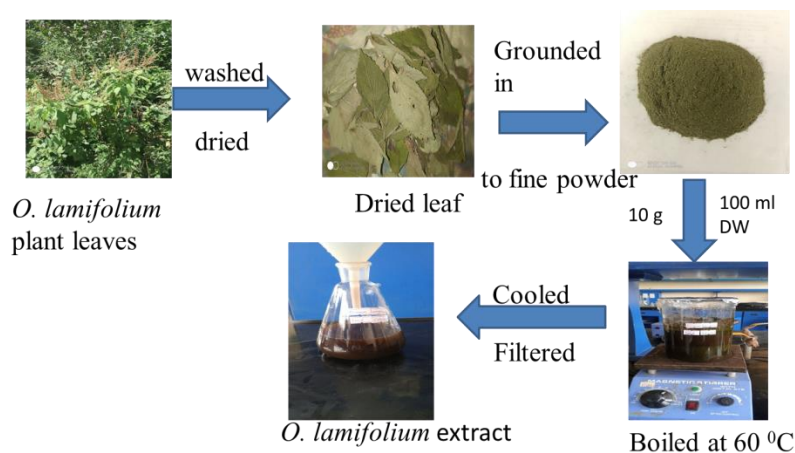


Figure 7. General procedure for the preparation of *Ocimum lamiifolium* leaf extract

3.5. Phytochemicals screening of the *Ocimum lamiifolium* leaf Extract

Phytochemicals are the bio-active elements which are present in the medicinal species (Chauhan *et al.*, 2024). The photochemistry assessment was performed using distinct chemical reagents and solutions to analyse the presence of the important active compounds of *Ocimum lamiifolium* leaf. The qualitative analysis of secondary metabolites were carried out using standard and previously reported procedures to identify various phytochemical constituents (Gebreslassie & Eyasu, 2019). Accordingly, the presence of alkaloids, flavonoids, phenols, tannins and saponins in the *Ocimum lamiifolium* leaf extract was examined.

a) Test for Alkaloids

Dragenderoff's Test: 2 ml aliquot of the extract was treated with the Dragenderoff's reagent. An orange red precipitates indicate the presence of alkaloids (Moaaz *et al.* , 2024).

b) Test for Flavonoids

Alkaline reagent Test: 1 ml of the extract was treated with 5 ml of sodium hydroxide. The formation of intense yellow colour precipitate confirms the presence of flavonoids (Roghini *et al.*, 2018).

c) Test for Tannins

Ferric chloride test: 1 ml of the extract was treated with few ml of 5% neutral ferric chloride. A dark blue or bluish black colour product shows the presence of tannins (Abdel-Fatah *et al.*, 2021).

d) Test for phenols

Ferric chloride test: 1 ml of the extract was treated with few ml of 5% neutral ferric chloride. A dark blue or bluish black colour product shows the presence of tannins (Abdel-Fatah *et al.*, 2021).

e) Test for Saponins

Frothing Test: About 1 ml of the extract was diluted separately with 20 ml of distilled water and shake in a graduated cylinder for 15 minutes. A 1 cm layer of foam indicates the presence of saponins (Berbers *et al.*, 2024)

3.6. Optimization of Reaction Parameters.

Optimization of Some reaction Parameters for Synthesis of *Ocimum lamiifolium* Leaf Extract Mediated CuO, Co₃O₄, NPs, and CuO/Co₃O₄ NCs. The quality, stabilization, quantity, and yield rate of nanoparticles are influenced by various parameters such as pH, temperature, ratio metallic precursor, and phytochemical profile of plant leaf particles.

a) Ratio of Metal Precursor: the synthesis of CuO/Co₃O₄ ncs was explored using copper to cobalt mole ratios (1:1, 1:2 and 2:1) to assess impact on absorption peak. For the above the reaction parameters the UV–visible spectrum was used to verify particle production, determining the best reaction conditions for nanoparticles and Nano composites.

b) pH of Reaction Medium: The effects of pH values of 4, 6, 8, 10, and 12 on the characteristics of the synthesized nanocomposite were investigated.

c) Volume of Leaf Extract: four different volumes of *ocimum lamiifolium* leaf (15mL, 20mL, 25mL and 30mL) were utilized to determine the optimal extract volume for capping and stabilization of nanocomposite

d) Temperature: the reaction was conducted at varying temperature (25°C, 60°C, 80°C and 100°C) to assess the influence of thermal on composite.

3.7. Green Synthesis of CuO NPs, Co₃O₄ NPs And CuO/Co₃O₄ NCs Using *Ocimum lamiifolium* Leaf Extract

3.7.1. Synthesis of CuO NPs Using *Ocimum lamiifolium* Leaf

Synthesis of CuO NPs capped with *Ocimum lamiifolium* leaf extract was conducted according to the reported literature with slight modifications (Mengesha *et al.*, 2024). 0.1M of copper sulphate pent hydrate (CuSO₄·5H₂O) was dissolved in 100 mL of deionized water. Meanwhile, 20 mL *Ocimum lamiifolium* leaf extract was added to the solution for the reduction of metal ions and at that temperature, the aqueous solution of NaOH (2 mol L⁻¹) was added drop wise until pH 12. The nanoparticle mixture of the solution was maintained at 60 °C for 2 h until the colour of the mixtures changed from green to brown solution. Stirred for 2hr cooled filtered

3.7.2. Synthesis of Co₃O₄ Nps Using *Ocimum Lamiifolium* Leaf Extract

For the Synthesis of cobalt oxide NPs, as reported (gendo *et al.*, 2024), freshly prepared plant extract (100 mL) was added to 0.1M solution (100 mL) of Co (NO₃)₂·6H₂O, and this reaction solution was kept on the hot plate for 2 hr at 80 °C to synthesize cobalt oxide nanoparticle with the pH 13. After 3 hr the solution was filtered and transferred into the oven at 70 °C for 5 hr to get the dried precipitate. Further, the precipitate of cobalt oxide NPs was calculated. Finally, synthesized Co₃O₄ NPs were characterized by spectroscopic and microscopic analysis.

3.7.3. Synthesis of CuO/Co₃O₄ NCs Nano Composite Using *Ocimum lamiifolium* Leaf Extract

Synthesis of CuO/Co₃O₄ Nano composites using *Ipomoea carnea* leaf extract was carried out based on the literature reports (Kumar *et al.*, 2024). With slight modifications. 1:2 mole ratio of 2.49 g(0.1M) of copper sulphate pent hydrate (CuSO₄·5H₂O) solution was prepared in 100 mL of deionized water. After its complete dissolution, 5.82 g(0.1M) of cobalt nitrate hexahydrate Co (NO₃)₂·6H₂O) was added to the copper solution. Then, 20 mL of *Ocimum lamiifolium* plant extract was mixed into the mixture of the solution. Added 2M of NaOH until the pH of CuO/Co₃O₄ NCs, 10 and the reaction mixture was

maintained at 80 °C for 2h until the colour of the mixture changed to brown, which indicates the formation of CuO/Co₃O₄ NCs. The resultant solution was kept at room temperature, washed with deionized water followed by absolute ethanol by centrifugation, and repeated two times. It was then allowed to air dry on a watch glass to produce its powder which was used for different characterizations.

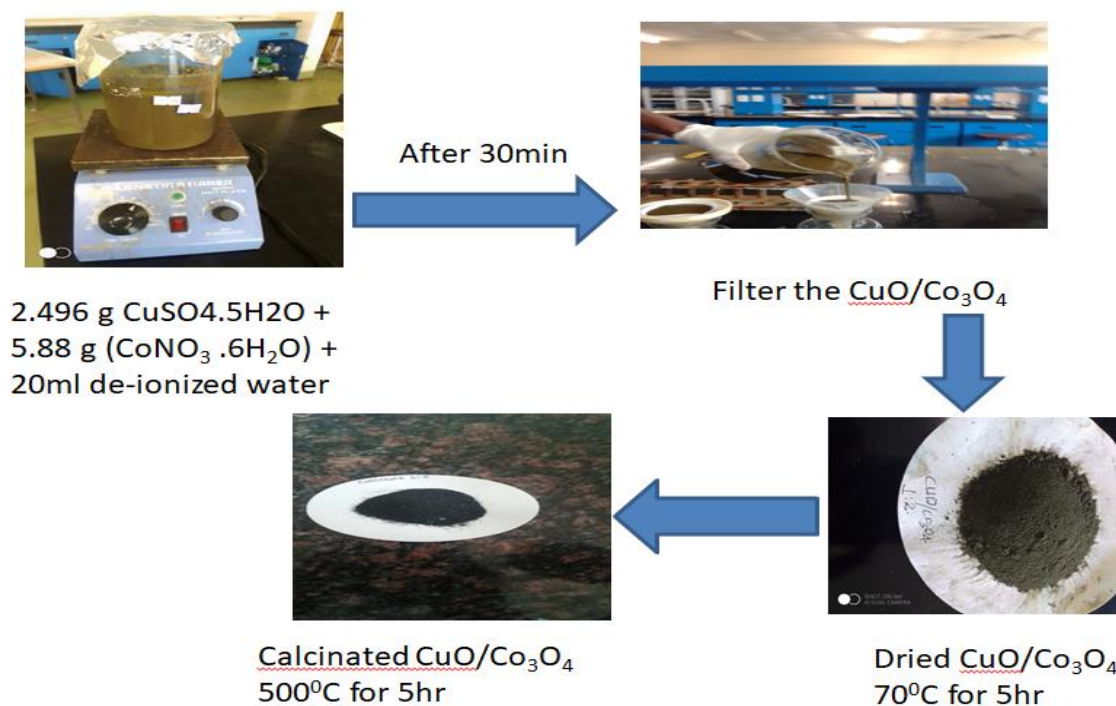


Figure 8. General procedure for the biosynthesis of copper oxide cobalt oxide Nanocomposite using *Ocimum lamifolium*.

3.8. Characterizations of the Synthesized CuO, Co₃O₄ NPs and CuO/Co₃O₄ NCs.

The synthesized nanoparticles and nanocomposites have been characterized using FTIR, UV- Vis and XRD spectroscopy techniques (Garg *et al.*, 2022).

3.8.1. UV-Visible Spectroscopy (UV-Vis)

The optical characterizations of CuO, Co₃O₄ NPs and CuO/Co₃O₄ NCs have been carried out using UV-Vis Spectroscopy in the wavelength region of 200 nm-800 nm. UV-Vis Spectroscopy was used in the range of 200–800 nm at room temperature in 1 cm path quartz cell, and the absorbance of the characteristic absorption peak for CuO, Co₃O₄ NPs and CuO/Co₃O₄ NCs, have been registered. The band gap value was obtained from the plot of the Kubelka–Munk function versus the energy of the absorbed light. The energy band gap would be calculated by the following formula (Landi *et al.*, 2022).

$$E_g = h\nu / \lambda \dots\dots\dots (5)$$

h = Plank's constant = 6.626×10^{-34} Js, $V = 3.0 \times 10^8$ m/s (speed of light) λ = wave length in nm.

E_g = Energy band gap

3.8.2. Fourier Transforms Infrared (FT-IR) Spectroscopy

The synthesized CuO, Co₃O₄ NPs and CuO/Co₃O₄ NCs have been characterized by FT-IR Spectrum in order to analyze and detect surface functional groups at the scanning range of 4000- 400 cm⁻¹. For the FT-IR characterization, the sample would be mixed with solid KBr uniformly and properly, then, compressed to settle down on a thin transparent film and this thin transparent film was used for FT-IR analysis which have been kept in the chamber of the instrument for scanning.

3.8.3. X-Ray Diffraction (XRD)

The crystalline size of the green synthesized CuO, Co₃O₄ NPs and CuO/Co₃O₄ NCs have been investigated by the X-ray diffraction using X-ray diffractometer (XRD). XRD spectrum would be recorded from 10 to 80 with 2 θ angles using CuK α (λ = 1.54 Å) radiation operated at 40kV and 30 mA. Debye Scherrer's equation indicated in equation 1, was used to estimate the crystallite size. (Alam *et al.*, 2024).

$$D = 0.94 \lambda / \beta \cos \dots\dots\dots (6)$$

3.9. Photo catalytic activity study

Firstly, 1000 mg/L of MB dye solution was prepared as a stock solution. From this stock solution, 10 mg/L was prepared in 100 mL of DI water. 0.3g of CuO/Co₃O₄ NCs catalysts were added into 100 ml of 10 mg/L of MB solution in a beaker. A mixture of the sample suspension was placed in the dark for 35 min and stirred with a magnetic stirrer to reach an adsorption desorption equilibrium between MB and the photo catalysts surface. After that, the sample suspensions were exposed to visible light (LED lamp, 220 Watt) at different time intervals (15, 30, and 45, 60, 75, 90 min) and 5 mL of sample suspensions obtained was withdrawn and centrifuged for fifteen min, and the absorbance of methylene blue in the resultant solution was monitored in the wavelength range of 400-800 nm in a UV-Vis spectrophotometer.. Distilled water was used as a reference. 1000ml of 10mg/ml

stirred magnetically for 35 min in darkness the suspension was irradiated under LED lamp for 90min The absorbance was recorded at 664 nm

The degradation efficiency (%) was calculated as follows (Zhang *et al.*, 2024)

$$\% \text{ Degradation} = \frac{A_0 - A_t}{A_0} \times 100 \dots \dots \dots (7)$$

Where, A_0 is absorbance of dye at initial stage and A_t is at a time “t”. The effect of different parameters like catalyst dosage, contact time, concentration of pollutant, effect of pH, and effect of irradiation time were studied during the degradation of MB dye by CuO/Co₃O₄ NCs. The catalytic activity of NPs was checked at optimum condition by following all the above procedure and compared with CuO/Co₃O₄ NCs.

3.10. Reusability of the Photocatalyst

The re-usability of CuO/Co₃O₄ NCs catalyst was performed using dye decomposition method under natural LED lamp (220 watt). 20 mg of CuO/Co₃O₄ NCs was added into a 250 mL beaker containing 100mL of MB solution (10 ppm). The mixture was stirred for 30 min at room temperature in the dark place to attain the adsorption-desorption equilibrium between the catalyst and MB (Lee *et al.*, 2024). 5 mL of the mixture was received, centrifuged for 10 min and its absorbance was measured in the range of 400-800 nm before illumination. The solution was then exposed to LED lamp (220 watt) under stirring. At 15 min interval, 5 mL of the solution was sampled, centrifuged and its absorbance was measured at maximum wavelength constantly. After fully decolorization, the photocatalyst was centrifuged, washed by distilled water repeatedly and dried at room temperature before applying for next time. Using the same procedure, the photocatalytic degradation valuations were carried out for three cycles under LED lamp (220 watt).

4. RESULT AND DISCUSSION

4.1. Phytochemical Screening of the *Ocimum lamiifolium* Leaf Extract

Phytochemical testing was undertaken to identify the secondary metabolite groups in the leaf extract of *Ocimum lamiifolium*. The preliminary results confirmed the presence of alkaloids, flavonoids, tannins, phenols, and saponins.

Table 1. Phytochemical components of *Ocimum lamifolium* leaf extract

Phytochemical secondary metabolites	Chemical test	Observation	Results
Alkaloids	Wagner's test	reddish-brown precipitate	++
Flavonoids	Lead acetate test	Brown colour was observed	+
Tannins	Ferric chloride test	blue-black color was formed	+
Phenols	Ferric chloride test	formation of dark green solution	+
Saponnins	De ionized water	formation stable froth that persists for at least 2 min	++

Remember: (+) indicates the presence of phytochemicals and (++) the highest phytochemicals.

The study revealed that the plant extract contains multiple classes of phytochemicals. The strong coloration observed in Wagner's test and in deionized water suggests a high concentration of alkaloids and saponins, respectively. The functional groups found in these compounds particularly hydroxyl (OH) and carbonyl (C=O) groups serve as both reducing and stabilizing agents in the formation of nanomaterials. These findings align well with the report by Khan *et al.* (2025), which also confirmed the presence of similar phytochemicals in *Ocimum lamiifolium* (Damakese) leaf extract (see Appendix 1).

4.2. Effects of Reaction Parameters on the Synthesis of CuO/Co₃O₄ NCs

a) Ratio of Metal Precursor

The 0.1 M was selected as the optimal precursor concentration for synthesizing CuO and Co₃ O₄ nanoparticles, as it produced a distinct absorption peak characteristic of nanoparticle formation. (Figure 9a) Different copper-to-cobalt molar ratios (1:1, 1:2, and

2:1) were then tested to identify the best reaction ratio. Among these, the 1:1 and 1:2 ratios were optimized because they generated the highest UV–Vis absorbance at longer wavelengths (red shift), indicating greater stability and yield.

b) pH of Reaction Medium

In this study, the pH of the solution was varied from 4 to 12 for CuO/Co₃O₄ NCs, whereas it was varied from 5 to 13 for Co₃O₄ NP synthesis to get optimum pH. For the acidic solution (pH = 5), no surface plasmon resonance (SPR) band of nanoparticles developed. However, changing the PH to alkaline resulted in the appearance of the SPR b and at distinct wavelengths. The intensity of UV-vis absorption increased as the pH of the reaction solution increased, owing to the increased concentration of the produced nanoparticles and Nano composites. This occurrence can be explained by the fact that high pH values enhance the creation of nucleation centres and increase the reduction of copper and cobalt into the corresponding metal oxide NPs, resulting in the synthesis of a large amount of NPs. (Figure 9b) a high-intensity peak was found in SPR at pH 10 for CuO/Co₃O₄ and Co₃O₄ NPs pH 13 were previus reported (gendo *et al.*, 2024). As a result of the acquired data, the pH values were optimized due to a better peak and maximum absorption peak intensity, and the rest of the studies were performed at the pH.

c) Volume of Leaf Extract

In a similar manner, different volumes of *Ocimum lamiifolium* leaf extract were used, and the results showed that as the volume of the extracted leaf increased from 10 to 25 mL, the absorption peaks decreased, with 20 mL of *Ocimum lamiifolium* leaf extract exhibiting the highest absorption. The concentration was increased to 20 mL because a strong peak with high intensity was observed (Figure9c). This shows that the presence of 20 mL of bioactive chemicals was sufficient to reduce metal ions in the reaction mixture and cap the nanoparticle surfaces by preventing their aggregation.

d) Temperature

To determine the ideal synthesis temperature, several temperatures (room temperature, 60, 80, and 100 °C) were evaluated, and 80 °C was found to be optimal for producing CuO/Co₃O₄ nanocomposites. This can be attributed to the faster reduction of metal ions at this temperature. However, increasing the temperature beyond this point led to a decrease

in absorption peak intensity, likely due to nanoparticle and nanocomposite aggregation caused by thermal degradation of plant-derived reducing and capping agents (Gendo *et al.*, 2024). After optimizing all parameters, green synthesis methods were employed to produce CuO and Co₃O₄ nanoparticles as well as CuO/Co₃O₄ nanocomposites.

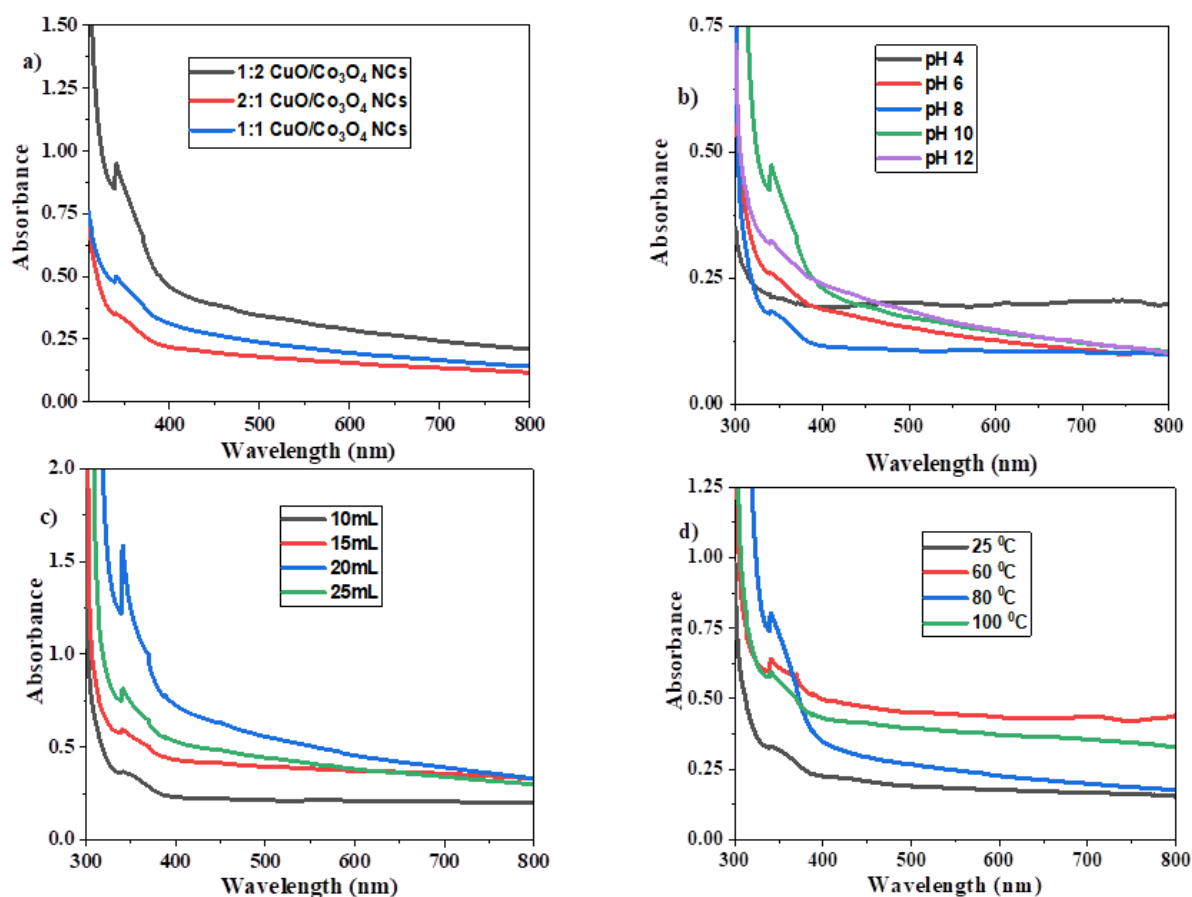


Figure 9. (a) 1:1, 1:2 and 2:1 of CuO/Co₃O₄ NCs, (b) PH, (1:2) (c) Temperature, (1:2) (d) Volume (1:)

4.3. Characterizations of the Synthesized CuO, Co₃O₄ NPs and CuO/Co₃O₄ NCs

4.3.1. UV-Vis spectroscopy Analysis

The optical characteristics of the biosynthesized CuO NPs, Co₃O₄ NPs, and the CuO/Co₃O₄ nanosystem are presented below. Figures 10(a) and 10(b) illustrate the absorption spectrum and the corresponding band gap for CuO nanoparticles. In the UV–Vis spectrum of the synthesized CuO NPs, a distinct surface plasmon resonance peak appears at 310 nm (Fig. 10a), with no additional peaks observed within the 200–800 nm range, and the peak exhibits a symmetrical profile. The surface plasmon absorption in

metal oxide nanoparticles arises from the collective oscillation of free conduction electrons induced by incident electromagnetic radiation. This resonance typically occurs when the wavelength of the incoming light is much larger than the nanoparticle diameter. The absorption maximum at 310 nm confirms the successful formation of CuO nanoparticles (El-Trass *et al.*, 2012).

The observed results are consistent with previously reported literature, which indicates that CuO nanoparticles typically exhibit surface plasmon resonance within the 200–350 nm range (Kong *et al.*, 2024). The findings obtained in this study closely align with these reported values. The band gap energy of the synthesized CuO NPs was calculated using Tauc's method, as illustrated in Figure 10(b), and the analysis revealed a band gap value of 3.2 eV..

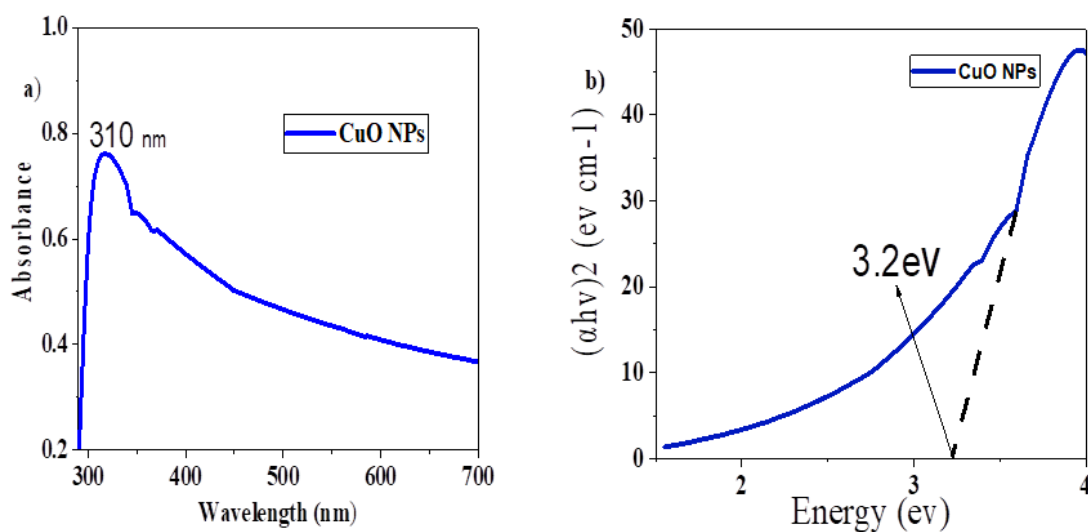


Figure 10. (a) Wavelength versus Absorbance of UV-Vis spectroscopy, (b) energy versus band gap of CuO NPs

The UV–Vis absorbance and band gap spectra of the phyto-mediated Co_3O_4 nanoparticles are presented in Figure 11(a) and 11(b). Characteristic absorption peaks appear at approximately 331 nm and 394 nm, which closely correspond to the values of 326 nm and 392 nm reported by Gendo *et al.* (2024). The broad first peak and the weaker second peak reflect charge-transfer transitions from oxygen to cobalt orbitals, indicating electron movement between $\text{Co}^{2+}/\text{Co}^{3+}$ and O^{2-} and confirming the presence of cobalt in two oxidation states. The calculated band gap of the biosynthesized Co_3O_4 nanoparticles was 3 eV, in good agreement with previously reported values (Shaheen *et al.*, 2022). This

relatively wide band gap suggests a significant separation between electrons and holes, limiting recombination. The resulting photoexcited charge carriers generate oxygen vacancies on the Co_3O_4 surface, which can enhance the degradation of organic pollutants and contribute to antibacterial activity in wastewater treatment and biomedical applications.

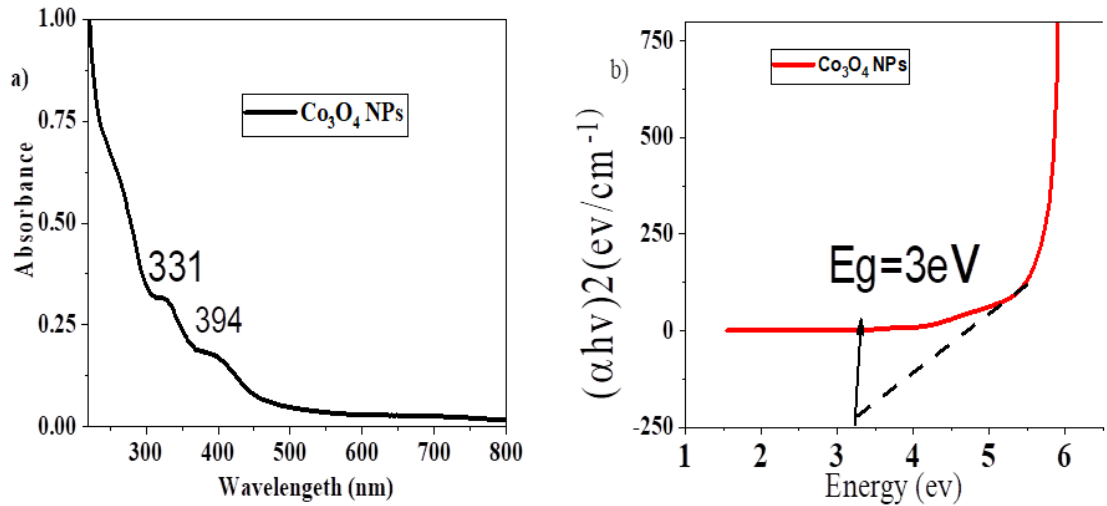


Figure 11. (a) Wavelength versus Absorbance of UV-Vis spectroscopy, (b) energy versus band

Figure 12(b) shows that the optical band gap of the $\text{CuO}/\text{Co}_3\text{O}_4$ composite is 2.5 eV. Compared to the individual metal oxide nanoparticles, the composite displays an overall increase in band gap. This enhancement suggests strong quantum confinement within the composite nanoparticles, which causes the conduction and valence band energy levels to move further apart, resulting in a blue shift in transition energy as particle size decreases (Katubi *et al.*, 2025).

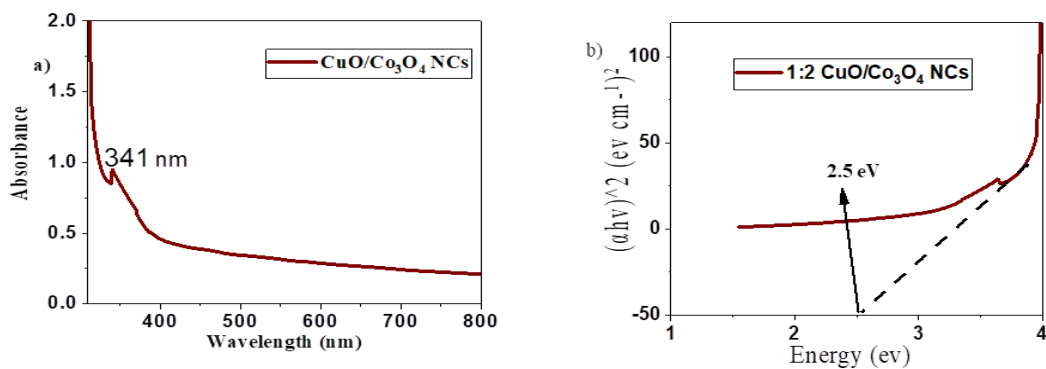


Figure 12. (a) Wavelength versus Absorbance of UV-Vis spectroscopy, (b) energy versus band the gap of $\text{CuO}/\text{Co}_3\text{O}_4$ composite NPs

4.3.2. Fourier Transform infrared (FT-IR) spectroscopy analysis.

FTIR analysis was conducted on the green-synthesized CuO NPs, Co₃O₄ NPs, the CuO/Co₃O₄ composite, and the *Ocimum lamiifolium* leaf extract to verify nanoparticle formation. This analysis also confirms that bioactive compounds in the extract played a key role as stabilizing and capping agents, helping to control the growth of the CuO, Co₃O₄, and composite nanoparticles. Figure 13(a) presents the FTIR spectrum of the *Ocimu lamiifolium* leaf extract. The spectrum exhibits absorption bands at 3353 cm⁻¹, 2924 cm⁻¹, 1603 cm⁻¹, 1512 cm⁻¹, 1374 cm⁻¹, 1264 cm⁻¹, 1036 cm⁻¹, and 912 cm⁻¹. The broad band near 3353 cm⁻¹ corresponds to O–H stretching vibrations, while the peak at 2924 cm⁻¹ indicates C–H stretching of alkanes. The absorption at 1603 cm⁻¹ is attributed to C=O stretching of carboxyl groups, and the peak around 1383 cm⁻¹ represents N–H bending of primary amines. Additionally, the band near 1035 cm⁻¹ is associated with C–O stretching of ether functional groups.

Figure 13(b) clearly shows noticeable peak shifts following the reaction between copper nitrate and the leaf extract. These shifts indicate that the functional groups present in the extract participated in binding to the CuO nanoparticles. The broad absorption band at 3129 cm⁻¹ corresponds to O–H stretching in alcohols and phenolic compounds, while the peak at 2075 cm⁻¹ represents C≡C stretching vibrations. The sharp band at 1387 cm⁻¹ is associated with the deformation vibration of C–H groups in alkanes (CH₃ and CH₂). Additionally, the peaks near 764 cm⁻¹ are characteristic of Cu–O stretching vibrations in monoclinic copper oxide nanoparticles (Sagadevan *et al.*, 2019).

Figure. 13(b) showed the absorption peaks of Co₃O₄ nanoparticles were observed at 3423 cm⁻¹, 2991 cm⁻¹, 1658 cm⁻¹, 1413 cm⁻¹, 1006 cm⁻¹, 862 cm⁻¹, 648 cm⁻¹, 552 cm⁻¹ and 3423 cm⁻¹, 2913 cm⁻¹, 1612 cm⁻¹, 1358 cm⁻¹, 1006 cm⁻¹, 696 cm⁻¹, 559 cm⁻¹ respectively. The absorption peak at 3423 cm⁻¹ corresponding to –OH stretching of the carboxylic acid. The absorption peak located at around 2991 cm⁻¹ reveals the presence of C-H stretching vibrations of alkane. The peaks located at 1658cm⁻¹ may be due to C=C stretching. The absorption peak revealed at 1413 cm⁻¹ and 1006 cm⁻¹ corresponds to the N=O Bend of the nitro group and C-O stretch of the ether functional group respectively. Moreover, the peaks at 659 cm⁻¹ and 569 cm⁻¹ showed the stretching vibration of Co–O, corresponding to the tetrahedral and octahedral coordination of Co²⁺ and Co³⁺, respectively (Zhai *et al.*, 2025). The absorption peaks of Co₃O₄ NPs and CuO/Co₃O₄ composite nanoparticles

were observed at 3256 cm^{-1} , 2157 cm^{-1} , 1658 cm^{-1} , 1444 cm^{-1} , 1097 cm^{-1} , 870 cm^{-1} 522 cm^{-1} .

The FT-IR spectrum of the CuO/Co₃O₄ composite nanoparticles displays a band at 3256 cm^{-1} , corresponding to C–H stretching of carboxylic acids. The band near 2913 cm^{-1} indicates C–H stretching vibrations of alkanes. Absorption peaks at 1612 cm^{-1} and 1358 cm^{-1} are attributed to the stretching and bending vibrations of the nitro (N=O) group, respectively. The peak around 1006 cm^{-1} corresponds to C–O stretching of ether groups, while the band at 696 cm^{-1} suggests the presence of substituted alkenes. Finally, the absorption at 559 cm^{-1} is associated with Co–O stretching in the CuO/Co₃O₄ composite nanoparticles (El-Sayed *et al.*, 2021).

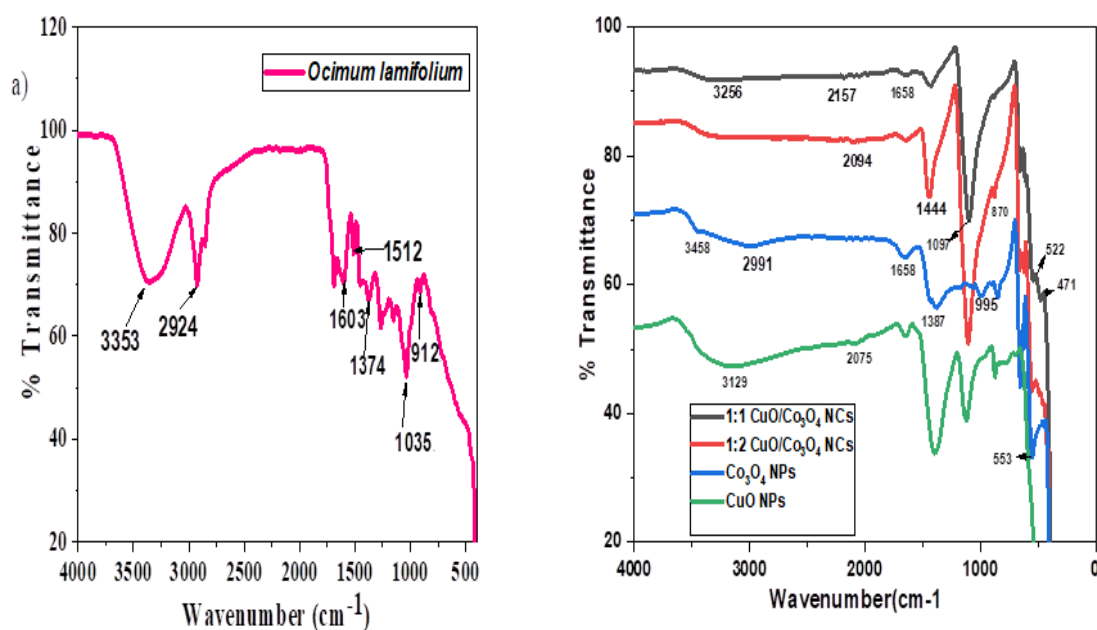


Figure 13. FTIR spectra of (a) *Ocimum lamiifolium* leaf extract, (b) CuO, Co₃O₄ NPs, and 1:1, 1:2 CuO/Co₃O₄ NCs

4.3.3. Powder X-ray diffraction (XRD) analysis results.

Powder XRD analysis was carried out to examine the structure and crystallinity of the synthesized CuO NPs, Co₃O₄ NPs, and CuO/Co₃O₄ composite nanoparticles. The XRD results of the prepared samples are shown in (Figure 15). The experimental patterns were compared with standard reference data for CuO and Co₃O₄. For CuO NPs, diffraction peaks appeared at 2θ values of 35.5°, 38.75°, 48.75°, 53.52°, 58.85°, 61.38°, 66.10°,

68.28°, 72.6°, and 75.38°, corresponding to the (110), (-111), (111), (200), (20-2), (002), (113), (220), (113), (311), and (004) planes, respectively, as shown in Figure 14(a). These results confirm that the synthesized CuO NPs possess a monoclinic phase, consistent with the JCPDS standard (Map #048-1548, space group C2/c), in agreement with previously reported findings (Tefera *et al.*, 2024). The XRD pattern of Co₃O₄ NPs is presented in Figure 14(b), with diffraction peaks observed at $2\theta = 18.99^\circ, 31.31^\circ, 36.88^\circ, 38.43^\circ, 44.86^\circ, 55.69^\circ, 59.42^\circ, \text{ and } 65.30^\circ$, corresponding to the (111), (220), (311), (222), (400), (422), (511), and (440) planes, respectively.

The spectral data obtained showed that the synthesized Co₃O₄ NPs showed cubic spinel crystal structure phase and the observed peaks were fitted with the Joint Committee on Powder Diffraction Standard (JCPDS card No. 042-1467, space group Fd-3m), which is in agreement with the previously reported work (Tefera *et al.*, 2024).

The XRD diffraction pattern of CuO/Co₃O₄ composite NPs is presented in Fig. 10 (c). The peaks at 2θ values $18.98^\circ, 31.57^\circ, 35.53^\circ, 36.85^\circ, 38.73^\circ, 44.78^\circ, 48.74^\circ, 59.35^\circ, \text{ and } 65.90^\circ$, corresponding to the miller indices (hkl) values of (111), (220), (311), (400), (200), (002), (440), (311), and (004) and respectively. The diffraction peaks at 2θ values of $53.54^\circ, 61.60^\circ, 72.40^\circ, \text{ and } 75.10^\circ$ are associated with the (20-2), (113), (311) and (004) planes of monoclinic phase CuO (JCPDS card No. 48-1548), and the peaks at 2θ values $18.99^\circ, 31.37^\circ, 36.85^\circ, 44.68^\circ, 65.90^\circ, \text{ and } 77.51^\circ$ correspond to the miller indices of (111), (220), (311), (400), (440), and (533) are planes of Co₃O₄ (JCPDS card No. 042-1467) confirming that the synthesized CuO/Co₃O₄ nanostructures have a crystalline structure. It can be seen that both CuO and Co₃O₄ peaks can be found in the sample. The relative intensities of the Co₃O₄ peaks decreased compared to those of the CuO peaks due to the formation of the CuO shell coating on the Co₃O₄ core surface.

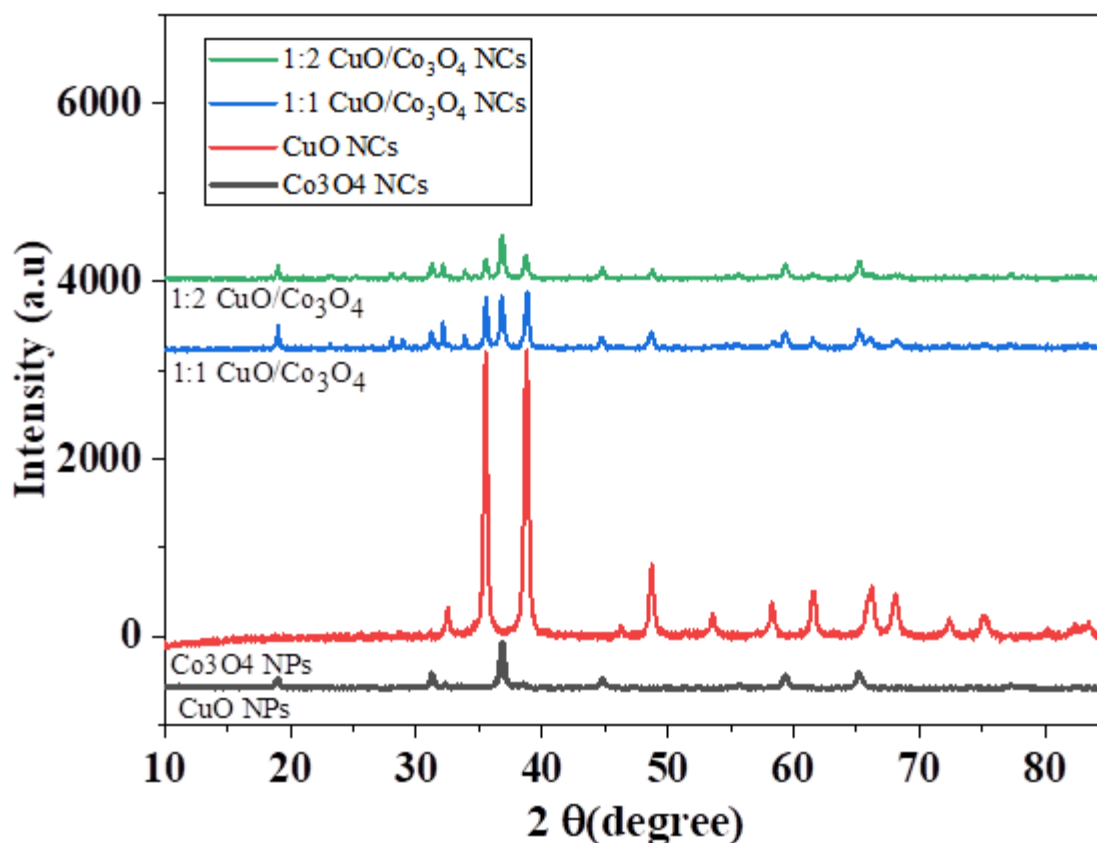


Figure 14. X-ray diffraction patterns a) CuO NPs, b) Co₃O₄ NPs, and c) CuO/Co₃O₄ composite

Table 2. The calculated parameters for the average crystalline size of CuO, Co₃O₄ NPs and 1:1, 1:2 CuO/Co₃O₄ NCs.

Samples	2 Theta(Degree)	FWHM	Crystalline Size	AverageCrystalline Size
CuO NPs	35.50268	7.20239	1.097180209	12.34 nm
	35.50268	0.35159	22.47595144	
	38.7565	0.41921	18.67157667	
	48.70566	0.45754	16.52117256	
	53.56055	0.59326	12.48592686	
	58.30794	0.56356	12.85791372	
	61.57381	0.52615	13.54761503	
	66.1173	0.82661	8.412829806	
	68.09104	0.69981	9.824297832	

	72.41373	0.63146	10.60250829	
	75.17373	0.70378	9.342521203	
Co ₃ O ₄ NPs	18.94535	0.34278	23.87603503	16.58 nm
	31.24039	0.40505	19.72825033	
	36.82419	0.44393	17.73392404	
	44.8109	0.53208	14.41700189	
	55.67061	0.47202	15.54448632	
	59.35802	0.54591	13.20521945	
	65.25197	0.60364	11.57661828	
1:1 CuO/Co ₃ O ₄ NCs	18.98584	0.21511	38.04446221	17.19 nm
	31.71339	1.53126	5.212464156	
	31.71339	0.31374	25.18459206	
	36.80958	0.38777	20.30315643	
	38.79331	0.4012	19.50754457	
	44.77579	0.37801	20.29567208	
	48.6697	0.48119	15.71140425	
	59.35042	0.48923	14.73567404	
	61.60809	0.48058	14.82959517	
	65.48871	1.38058	5.055015168	
	68.22119	0.66908	10.26762335	
1:2 CuO/Co ₃ O ₄ NCs	18.98531	0.23252	35.19589969	19.19 nm
	31.59277	1.34285	5.945578299	
	35.53801	0.34914	22.63143563	
	36.81926	0.40216	19.57612304	
	38.73117	0.46285	16.91243389	
	44.78918	0.37711	20.34312979	
	48.76195	0.31385	24.07970586	
	59.35804	0.49669	14.51380263	
	65.23753	0.51905	13.46435513	

4.4. Factors Affecting Photo catalytic Activity

4.4.1. Effect of PH

One of the most vital factors in photo catalytic processes is the pH of the solution. It has a considerable impact on the charges on the catalyst surface, which greatly influences photo catalytic activity. The pH of the MB solution was changed by adding 0.1 M HCl or NaOH. To investigate the influence of pH on the photo catalytic degradation of MB dye, separate experiments were carried out at pH values ranging from 4 to 12, with a constant dye concentration (10 ppm), irradiation time (90min), and catalyst amount (0.3g/L, as shown in Figure 15b). The degradation of MB dye increased as the pH was increased from 4 to 10. The CuO/Co₃O₄ NCs with molar ratio of 1:1 and 1:2 exhibited maximum degradation efficiency of 95% and 96.13 %, respectively. The increase in photocatalytic degradation efficiency with rising pH is likely due to the higher availability of hydroxyl ions (OH⁻) in the alkaline medium, which combine with holes formed during the electronic excitation of the catalyst to generate more hydroxyl radicals, which are highly reactive species responsible for the degradation of methylene blue. In contrast, the lower removal efficiency observed under acidic condition may be attributed to the higher concentration of H⁺ ions, which repel the MB dye molecules and reduce their interaction with the catalyst's active sites.

4.4.2 Catalyst dosage

The amount of organic pollutants adsorbed on the surface of nanoparticles is a key factor affecting their photocatalytic efficiency. A period of equilibration in the dark is necessary, as photocatalytic degradation of pollutants primarily occurs in the adsorbed phase. As shown in Figure 15(a), increasing the CuO/Co₃O₄ nanocatalyst dosage from 10 mg to 20 mg and 30 mg led to an increase in degradation efficiency from 54%, 63.7%, to 83%, respectively. This improvement is attributed to the higher catalyst dosage providing more active sites and generating more reactive radicals, thereby enhancing the photodegradation of methylene blue dye. Further increasing the catalyst amount to 40 mg resulted in degradation of MB becomes decreased slowly due to the enhancement of light reflectance by the catalyst owing to weaker penetration of light.

4.4.3. Effect of initial MB dye concentration

The initial dye concentration is a key factor influencing photocatalytic degradation efficiency. The effect of varying methylene blue (MB) concentrations on its decolorization was investigated under visible light (220 Watt LED lamp) using 30 mg of CuO/Co₃O₄ nanocomposites at an optimal pH of 10. As illustrated in Figure 15(c), the degradation efficiency of MB decreases from 81% to 60% as the initial dye concentration increases from 10 mg/L to 40 mg/L. Similar results were reported by literature (gendo *et al.*, 2024) that increasing the dye concentration cause the dye molecules to absorb light and the photons never reached the CuO/Co₃O₄ surface, and at high dye concentrations more active sites may be covered with dye ions. This may lead to the decrease in the production of OH radicals on the surface of the catalyst which plays a significant role in the dye degradation and finally it causes reduced efficiency of dye removal (Iqbal *et al.*, 2024). Thus, the photo-degradation of MB was found better at low concentrations.

4.4.4. Effect of Irradiation Time.

The effect of irradiation time on the photocatalytic degradation efficiency of the catalyst for MG dye was investigated over a reaction period of 0 to 105 minutes under optimized conditions, using a dye concentration of 10 ppm, a catalyst loading of 0.3 mg, and a pH of 10. The results are presented in Figure 15(d). The adsorption-driven degradation of the dye on nanosized CuO/Co₃O₄ was initially slow but accelerated as the contact time increased. Complete decolorization of the dye was achieved within 90 minutes, after which the degradation reached a saturation point. Therefore, the optimal irradiation time for maximum dye removal is 90 minutes. This is due to the fast adsorption rate before equilibrium; this may be explained by an increase in the number of active binding sites on the photocatalyst surface. Because there are fewer accessible sorption sites at the equilibrium stage, adsorption is most likely an attachment controlled process. The corresponding degradation proficiency of MB was found to be 84.18 and 89.36% by 1:1 and 1:2 CuO/Co₃O₄ NCs, respectively at PH 10.

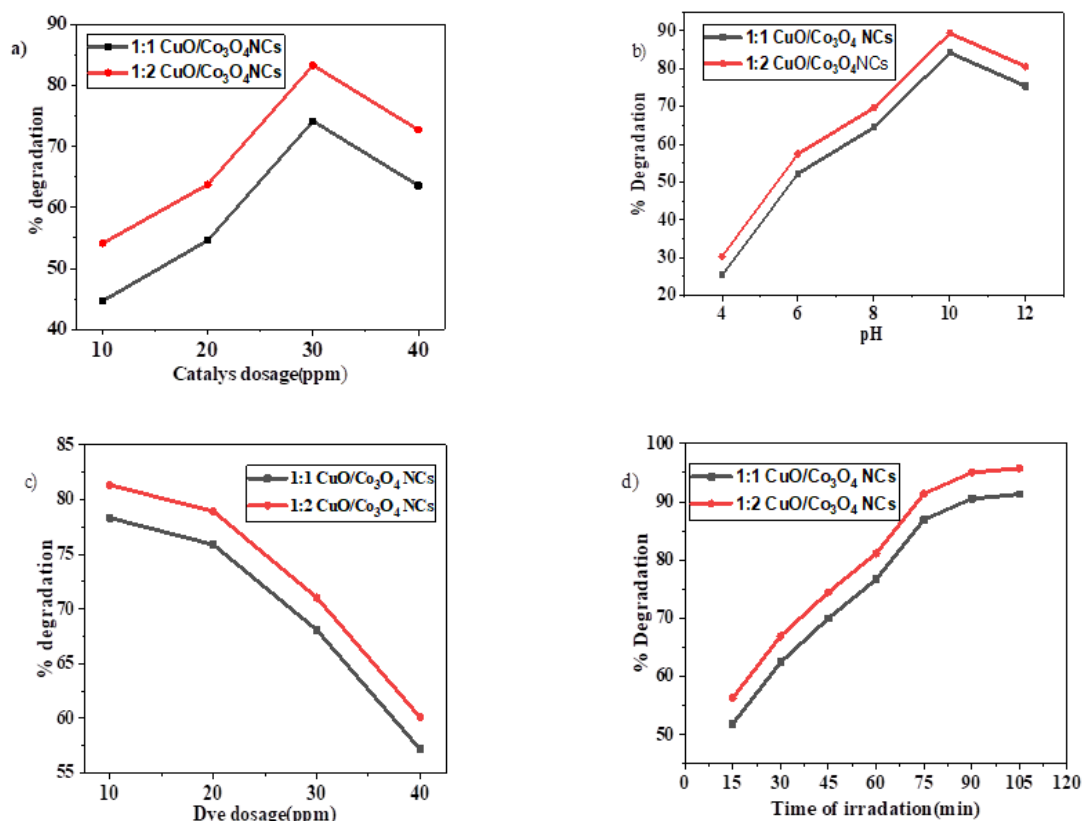


Figure 15. Optimization of (a) catalytic dosage, (b) pH, (c) initial dye concentration, and (d) irradiation time for MB degradation using CuO/Co₃O₄ NCs

4.5. Evaluation of Photocatalytic Activities of Green Synthesized CuO, Co₃O₄ NPs and CuO/Co₃O₄ NCs for Degradation of MB Dye.

The photocatalytic activity of the synthesized CuO, Co₃O₄ NPs, and CuO/Co₃O₄ NCs was evaluated using MB dye as a model pollutant under sunlight as a source of visible light, and the result is summarized in Figure (16a-d). With an increasing irradiation time, the absorbance spectra of the MB dye solution decreased continuously. The reduction in absorbance showed dye decolorization due to chromophore cleavage. Decreases in intensity confirm the photocatalytic degradation of the dye. At 30 min, the intensity of all peaks in Figure 16 is slightly reduced even in the dark, which could be due to the partial adsorption of MB dye molecules on the surface of the photocatalyst. After 40 min of radiation exposure, the dye color diminished significantly, and after 90 min of reaction, the decolorization achieved up to 96.134% for 10 ppm dye utilizing 30mg CuO/Co₃O₄ NCs. All samples show a high percentage of degradation of the MB dye, as indicated in Figure 17. Green synthesized CuO, Co₃O₄ NPs, 1:1 and 1:2, mol ratios of CuO/Co₃O₄

NCs revealed good photocatalytic activities with degradation efficiencies of 84.10403, 85.13702, 95 and 96.134%, respectively, after 90 min of irradiation. CuO/Co₃O₄ NCs (1:2) showed a high percentage degradation up to 96.13%, which revealed the highly efficient activity of CuO/Co₃O₄ NCs for the degradation of MB dye. The high photoactivity of the nanocomposite could be achieved by the green synthesis of CuO/Co₃O₄ NPs. CuO, Co₃O₄, NPs 1:1 and 1:2 CuO/Co₃O₄ NCs with degraded 84.1, 85.14, 95 and 96.134% respectively.

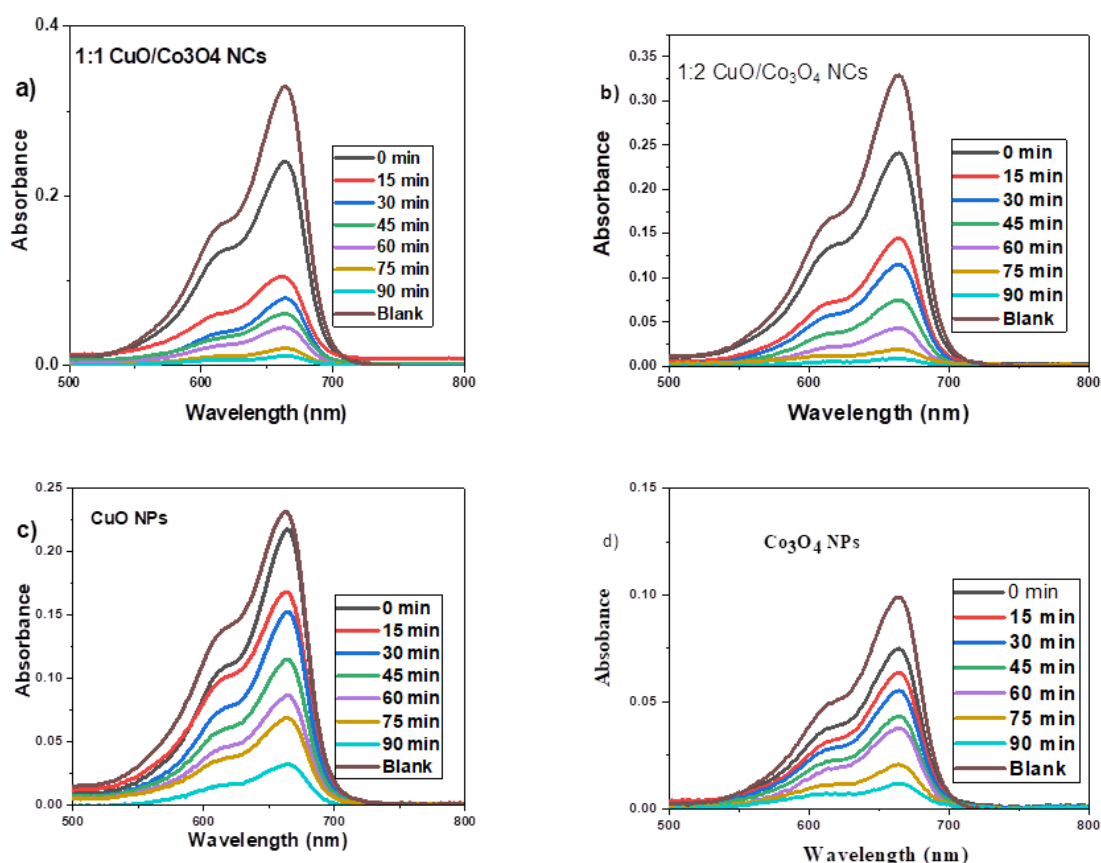


Figure 16. UV vis spectrum of photocatalytic degradation of MB using (a)1:1CuO/Co₃O₄ NCs, (b) 1:2 CuO/Co₃O₄ NCs, (c) CuO NPs and (d) Co₃O₄ NCs.

4.6. Reusability of Photocatalyst (CuO/Co₃O₄ NCs).

The study investigates the reusability of CuO/Co₃O₄ NCs photo catalysts for long-term heterogeneous catalysis. The catalysts were collected, washed, dried, and reused for aqueous phase degradation of MB dye under optimum conditions (pH = 10, initial concentration of MB = 10 ppm, and catalyst load = 0.3g/L), and the results are compiled in Figure 17. The photo degradation percentages of MB for the three successive cycles of CuO/Co₃O₄ NCs were 86.82109, 85.70288, and 85.56976%, respectively.

ively. Results showed a modest decrease in photo catalytic activity after three cycles due to the deposition of adsorbed MB molecules on the catalyst surface (Alaya *et al.*, 2024). According to the findings, CuO/Co₃O₄ NCs are reusable photo catalysts for the degradation of MB dyes.

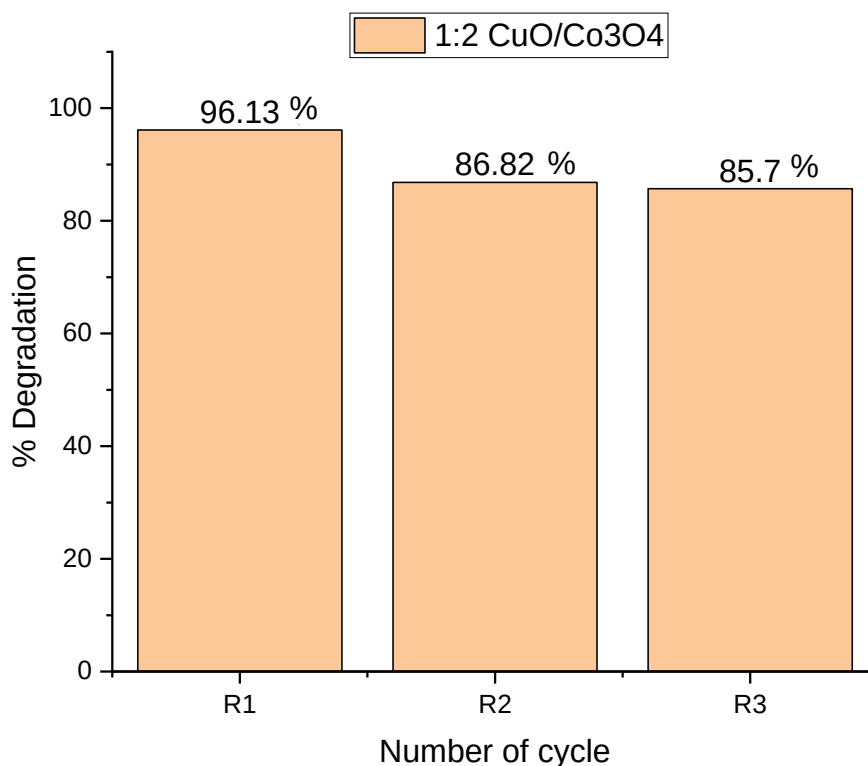


Figure 17. Reusability of CuO/Co₃O₄ NCs for the photodegradation of MB for three successive MB cycles

4.7. Possible Mechanism of MB Dye Degradation by CuO/Co₃O₄ NCs

The reaction mechanism for the degradation of the MB dye by CuO/Co₃O₄ NCs was proposed as indicated in Figure 18 . The degradation of MB dye by CuO/Co₃O₄ NCs is mainly due to the generation of electrons and holes (e⁻ and h⁺) on the catalyst surface under irradiation. The band structure of the heterostructures permits the transfer of electrons from CB of Co₃O₄ to CB of CuO and transfer of holes from VB of CuO to VB of Co₃O₄, as shown in below equation. Therefore, the recombination of electron-hole pairs will be hindered and the photocatalytic property would be improved. The holes transferred to cobalt oxides are trapped by H₂O and OH⁻ to further produce ·OH and OH⁻.

species. On the basis of this discussion, the proposed mechanisms in expression form are as follows: MB + other product

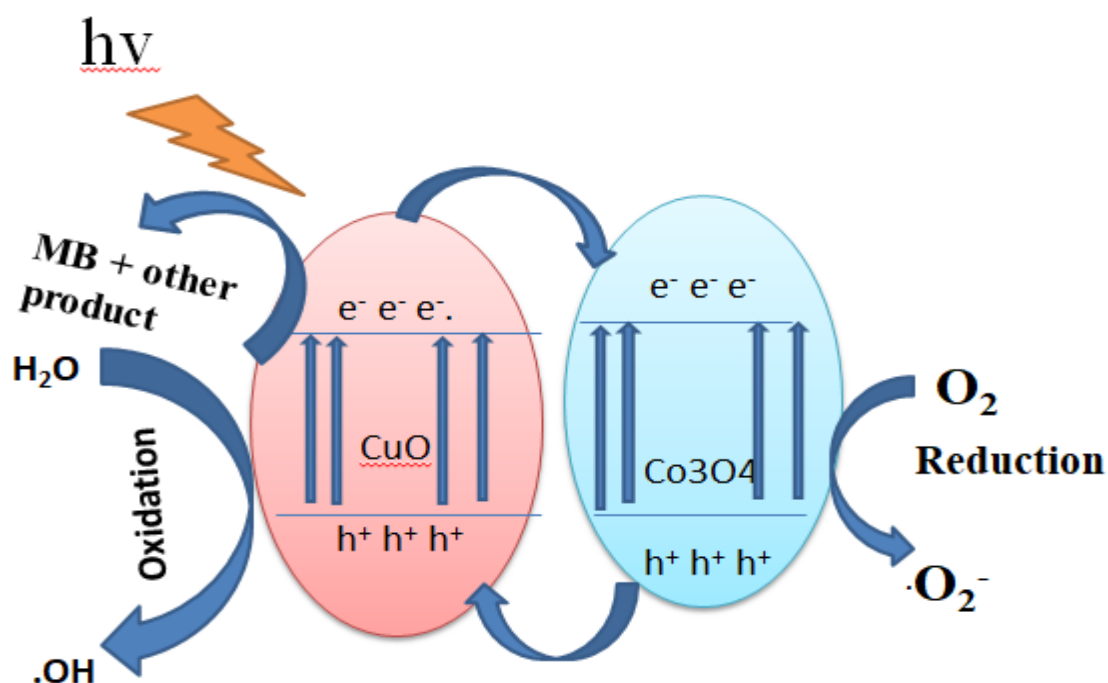
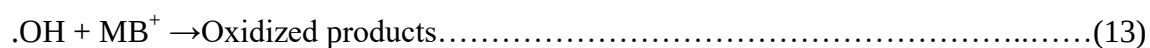
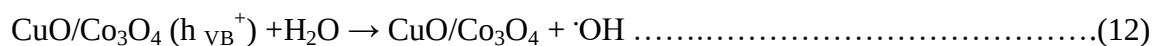
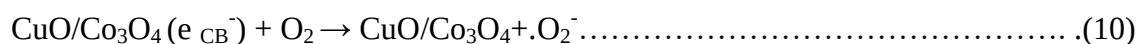
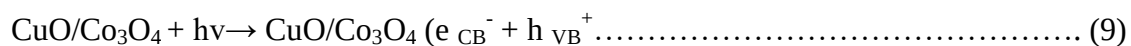


Figure 18. Proposed mechanism of photocatalytic degradation for MB dye under LED lamp (watt 220) using the CuO/Co3O4 catalys

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

In this study, CuO NPs, Co₃O₄ NPs and CuO/Co₃O₄ NCs were successfully synthesized from copper sulphate and cobalt nitrate using *ocimum lamiifolium* leaf extract as a capping and reducing agent. The synthesized Nano composites were characterized by UV-Vis, FT-IR, and XRD. The Synthesis of CuO/Co₃O₄ Nano composites were optimized by some parameters like pH, metal ion concentration, the volume of extract, temperature, and reaction time to identify the effect of those parameters on the surface synthesis of the Nano composite. The FT-IR spectroscopy revealed the presence of possible functional groups in the synthesized CuO NPs, Co₃O₄ NPs and CuO/Co₃O₄ NCs that played as capping and reducing agent. The XRD results showed the synthesized nanocomposite have a crystalline structure. The effect of parameters like catalyst dose, dye concentration, and pH on the photocatalytic degradation of MB dye was studied and optimized. The photocatalytic degradation of CuO/Co₃O₄ NCs was investigated using methylene blue dye in the presence of LED lamp (watt 220) and the results ensured a drastic improvement from the earlier reports of the photocatalytic activity of CuO/Co₃O₄ NCs. Hence, the designed plant leaf mediated CuO/Co₃O₄ NCs synthesis have provided avenues with the enhancement of high-efficiency of its photocatalytic degradation activity, so that the desired objectives were fruitfully attained.

5.2. Recommendations

- From this study, the following recommendation has been forwarded:
- Additional characterization is significant for the surface morphology, distribution, composition, stability, moisture content, size and shape of the synthesized CuO/Co₃O₄ NCs using SEM, TEM, EDX and TGA techniques.
- It is also recommended that the synthesized CuO/Co₃O₄ NCs needs additional study for more applications like sensor and antimicrobial activity.

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Appendix 1. Phyto-chemicals present in *Ocimum lamiifolium* plant extract