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Eco-Engineered CuO–SrO Nanocomposites via Evolvulus alsinoides: A Sustainable Route to Multifunctional Antibacterial Nanomaterials

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Abstract: The present study reports the green synthesis of CuO–SrO nanocomposites using the aqueous extract of Evolvulus alsinoides as a natural reducing and stabilizing agent. The proposed plant-mediated synthesis offers an environmentally benign, cost-effective, and sustainable alternative to conventional chemical methods by eliminating the use of hazardous reagents. The synthesized nanocomposites were characterized by UV–Visible spectroscopy to confirm their optical properties and successful formation. A characteristic absorption band observed in the 270–310 nm region indicated the formation of CuO–SrO nanocomposites through charge-transfer transitions between the constituent metal ions and oxygen. The antibacterial efficacy of the synthesized nanocomposites was evaluated against both Gram-positive (Bacillus subtilis, Bacillus cereus, and Staphylococcus albus) and Gram-negative (Escherichia coli, Pseudomonas aeruginosa, and Klebsiella pneumoniae) bacterial strains using the disc diffusion method. The CuO–SrO nanocomposites exhibited significant broad-spectrum antibacterial activity, with the highest zone of inhibition recorded against Pseudomonas aeruginosa (22 mm), followed by Staphylococcus albus (21 mm) and Klebsiella pneumoniae (20 mm). The enhanced antibacterial performance is attributed to the synergistic interaction between CuO and SrO, which promotes reactive oxygen species generation and membrane disruption. Overall, this work demonstrates that Evolvulus alsinoides-mediated CuO–SrO nanocomposites are promising multifunctional nanomaterials with potential applications in antimicrobial coatings, environmental remediation, and other biomedical technologies.

***Index Terms* -** Green synthesis; Evolvulus alsinoides; CuO–SrO nanocomposites; Antibacterial activity; Metal oxide nanoparticles.

Introduction

Nanotechnology has revolutionized modern materials science by enabling the development of materials with unique physicochemical properties at the nanoscale. Owing to their high surface-to-volume ratio, quantum confinement effects, and enhanced surface reactivity, nanomaterials exhibit superior optical, electrical, catalytic, and biological properties compared to their bulk counterparts [1,2]. These distinctive characteristics have led to widespread applications in environmental remediation, catalysis, energy storage, sensing, drug delivery, and biomedical engineering [3]. Among various nanomaterials, metal oxide nanoparticles have attracted considerable attention because of their excellent chemical stability, cost-effectiveness, tunable electronic properties, and multifunctional applications [4]. Copper oxide (CuO) is a p-type semiconductor with a narrow band gap (1.2–1.9 eV), high catalytic activity, and excellent antimicrobial properties. CuO nanoparticles have been widely investigated for applications in photocatalysis, gas sensing, lithium-ion batteries, solar cells, wastewater treatment, and antimicrobial coatings [5,6]. Their ability to generate reactive oxygen species (ROS) contributes significantly to their antibacterial and photocatalytic performance. However, pure CuO nanoparticles often exhibit particle agglomeration and rapid recombination of photogenerated electron–hole pairs, which limit their catalytic efficiency and practical applications [7]. To overcome these drawbacks, researchers have focused on fabricating binary metal oxide nanocomposites that exhibit enhanced physicochemical properties through synergistic interactions between their constituent metal oxides. Strontium oxide (SrO) is an alkaline earth metal oxide known for its high thermal stability, strong basicity, excellent ionic conductivity, and chemical stability [8]. It has been employed in catalysis, environmental remediation, dielectric materials, and biomedical applications. Incorporation of SrO into CuO forms CuO–SrO nanocomposites with improved crystallinity, enhanced charge separation, increased oxygen vacancies, and better structural stability [9]. These synergistic effects significantly enhance photocatalytic efficiency, antimicrobial activity, and electron transport properties, making CuO–SrO nanocomposites promising materials for environmental and biomedical applications [10]. The multifunctional behavior of CuO–SrO nanocomposites has therefore attracted increasing research interest for developing sustainable advanced functional materials. Conventional synthesis methods such as sol–gel, hydrothermal, combustion, and chemical precipitation generally require hazardous reducing agents, toxic solvents, and high-temperature processing, which increase production costs and generate environmentally harmful by-products [11]. In response to growing environmental concerns, green synthesis has emerged as a sustainable alternative for nanoparticle production. Plant-mediated synthesis utilizes naturally occurring phytochemicals as reducing and stabilizing agents, eliminating the need for toxic chemicals while offering a simple, economical, and environmentally friendly approach [12,13]. Bioactive compounds such as flavonoids, phenolics, alkaloids, terpenoids, tannins, and saponins reduce metal ions into nanoparticles while simultaneously preventing particle agglomeration through surface capping, resulting in stable nanomaterials with controlled morphology and enhanced biological activity [14]. Evolvulus alsinoides (L.) L., a medicinal herb belonging to the family Convolvulaceae, is widely recognized in traditional Ayurvedic medicine for its antioxidant, anti-inflammatory, antimicrobial, neuroprotective, and adaptogenic properties [15]. The plant contains diverse phytochemicals including flavonoids, phenolic acids, alkaloids, coumarins, steroids, glycosides, and terpenoids that possess strong reducing and antioxidant capabilities [16]. These phytochemicals effectively facilitate the reduction of Cu^{2+} and Sr^{2+} ions and stabilize the synthesized nanocomposites, resulting in improved crystallinity, morphology, and biological performance. Consequently, E. alsinoides has emerged as an attractive natural resource for the green synthesis of multifunctional metal oxide nanomaterials. The increasing prevalence of multidrug-resistant microorganisms has intensified the search for novel antimicrobial materials with improved efficacy and reduced toxicity [17]. Metal oxide nanoparticles have demonstrated broad-spectrum antibacterial activity through mechanisms including reactive oxygen species generation, disruption of bacterial cell membranes, leakage of intracellular components, and interference with DNA and protein synthesis [18]. The combination of CuO and SrO further enhances these mechanisms through synergistic effects that improve nanoparticle stability, surface reactivity, and ROS production, thereby increasing antibacterial efficiency against both Gram-positive and Gram-negative bacteria [19]. Such properties make CuO–SrO nanocomposites attractive candidates for antimicrobial coatings, wound dressings, water purification, and biomedical devices. Although several studies have reported the green synthesis of CuO nanoparticles and various binary metal oxide nanocomposites, investigations on Evolvulus alsinoides-mediated CuO–SrO nanocomposites remain limited. Moreover, comprehensive studies correlating green synthesis with structural, optical, and antibacterial properties are still scarce [20,21]. Therefore, the present study focuses on the green synthesis of CuO–SrO nanocomposites using aqueous extract of Evolvulus alsinoides as a natural reducing and capping agent. The synthesized nanocomposites are characterized using appropriate analytical techniques, and their antibacterial activity is evaluated against selected Gram-positive and Gram-negative bacterial strains. This work aims to develop an environmentally benign synthesis strategy for producing stable, multifunctional CuO–SrO nanocomposites with potential applications in environmental remediation and biomedical fields.

II LITERATURE REVIEW

Copper oxide (CuO) nanoparticles have attracted significant research interest because of their excellent optical, catalytic, and antimicrobial properties. Their narrow band gap, high surface area, and chemical stability make them suitable for photocatalysis, environmental remediation, energy storage, and biomedical applications. However, pure CuO nanoparticles often suffer from particle agglomeration and rapid electron–hole recombination, which limit their practical performance (Chakraborty et al. [22]; Millavithanachchi et al. [23]). Recent studies have demonstrated that green synthesis using plant extracts offers an effective strategy for producing CuO nanoparticles with improved stability, controlled morphology, and enhanced biological activity. The development of binary metal oxide nanocomposites has further improved the functional properties of CuO nanoparticles. Incorporation of strontium oxide (SrO) enhances crystallinity, thermal stability, and charge carrier separation, resulting in improved photocatalytic and antibacterial performance. The synergistic interaction between CuO and SrO creates heterojunction interfaces that facilitate electron transport and suppress charge recombination, thereby increasing catalytic efficiency and antimicrobial activity (Rani et al. [24]). These multifunctional nanocomposites have shown promising applications in wastewater treatment, antimicrobial coatings, and environmental remediation. Green synthesis has become an attractive alternative to conventional chemical methods because it utilizes plant-derived phytochemicals as natural reducing and stabilizing agents. Flavonoids, phenolics, alkaloids, terpenoids, and tannins not only reduce metal ions but also prevent nanoparticle aggregation, producing stable nanomaterials with enhanced physicochemical properties (Osman et al. [25]; Verma et al. [26]). Recent investigations have reported that plant-mediated CuO nanoparticles exhibit superior photocatalytic degradation efficiency and stronger antibacterial activity than chemically synthesized nanoparticles due to the presence of bioactive phytochemical residues on the nanoparticle surface. Although numerous medicinal plants have been employed for nanoparticle synthesis, reports on Evolvulus alsinoides-mediated CuO–SrO nanocomposites remain scarce. Therefore, the present study explores the use of Evolvulus alsinoides extract as a green reducing and capping agent for synthesizing CuO–SrO nanocomposites and evaluating their optical and antibacterial properties, providing a sustainable approach for developing multifunctional nanomaterials for environmental and biomedical applications.

III. MATERIALS AND METHODS

3.1 Materials

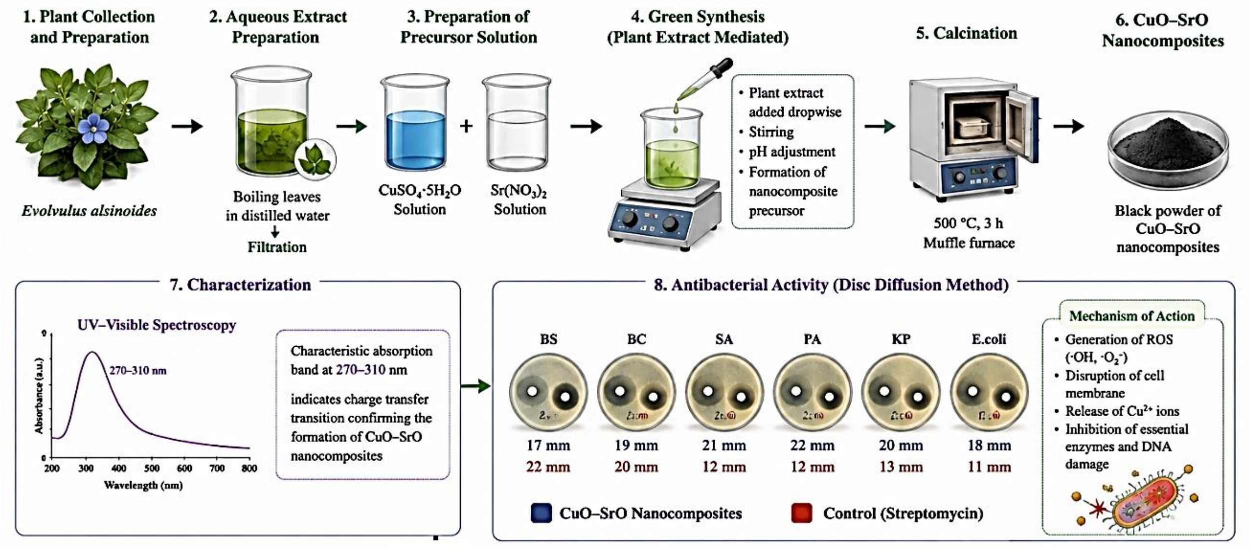
Analytical-grade copper(II) nitrate trihydrate [$Cu(NO_3)_2 \cdot 3H_2O$] and strontium nitrate [$Sr(NO_3)_2$] were used as metal precursors for the synthesis of CuO–SrO nanocomposites. Ethanol, sodium hydroxide, and double-distilled water were used throughout the experimental work without further purification. Fresh Evolvulus alsinoides plants were collected from the college campus and used as the natural reducing and stabilizing agent for the green synthesis.

3.2 Preparation of Evolvulus alsinoides Extract

The collected plant material was thoroughly washed with tap water followed by double-distilled water to remove dust and impurities. The cleaned plant material was shade-dried at room temperature for 14 days and ground into a fine powder. Approximately 10 g of the powdered sample was mixed with 200 mL of double-distilled water and heated at 80 °C for 2 h under continuous stirring. After cooling to room temperature, the extract was filtered using Whatman No. 1 filter paper and stored at 4 °C for further use.

3.3 Green Synthesis of CuO–SrO Nanocomposites

CuO–SrO nanocomposites were synthesized by a plant-mediated co-precipitation method. Equal volumes of 0.1 M aqueous solutions of copper(II) nitrate and strontium nitrate were mixed under constant magnetic stirring and heated to 70 °C. The prepared Evolvulus alsinoides extract was added dropwise to the mixed metal precursor solution under continuous stirring. The pH of the reaction mixture was adjusted to approximately 10 using sodium hydroxide solution to facilitate the formation of mixed metal hydroxide precursors. The reaction was maintained under stirring for 2 h to ensure complete precipitation. The resulting precipitate was separated by filtration, washed repeatedly with double-distilled water followed by ethanol to remove residual impurities and phytochemicals, and dried in a hot-air oven at 90 °C overnight. The dried precursor was then calcined at 450 °C for 3 h in a muffle furnace to obtain crystalline CuO–SrO nanocomposites (**Scheme-1**).



Scheme-1. Green Synthesis of CuO–SrO Nanocomposites

3.4 Characterization

The optical properties of the synthesized CuO–SrO nanocomposites were examined using a UV–Visible spectrophotometer over the wavelength range of 200–800 nm.

3.5 Antibacterial Activity

The antibacterial activity of the synthesized CuO–SrO nanocomposites was evaluated by the disc diffusion method against both Gram-positive (Bacillus subtilis, Bacillus cereus, and Staphylococcus albus) and Gram-negative (Escherichia coli, Pseudomonas aeruginosa, and Klebsiella pneumoniae) bacterial strains. Fresh bacterial cultures were prepared in nutrient broth and incubated at 37 °C for 24 h. Sterile filter paper discs loaded with different concentrations of the nanocomposite suspension were placed on nutrient agar plates inoculated with the test microorganisms. Streptomycin was used as the positive control, whereas dimethyl sulfoxide (DMSO) served as the negative control. After incubation at 37 °C for 24 h, the zones of inhibition were measured in millimeters to determine the antibacterial efficacy of the synthesized CuO–SrO nanocomposites.

IV. RESULTS AND DISCUSSION

4.1. Characterization of Evolvulus alsinoides extract.

Evolvulus alsinoides (Linn.), commonly known as Shankhpushpi, is a perennial herb belonging to the Convolvulaceae family. Phytochemical analyses reveal the presence of alkaloids, flavonoids, steroids, saponins, tannins, and glycosides responsible for its diverse pharmacological activities (Table-1). It exhibits antioxidant, anti-inflammatory, nootropic, antidiabetic, and antimicrobial properties, supporting its traditional use in Ayurveda for cognitive enhancement and nervous disorders. Cross-sectional phytochemical studies indicate significant variations in bioactive compound concentration depending on geographical and seasonal factors. Morphologically, it is characterized by small blue flowers, slender stems, and oblong leaves. Its ethanolic and aqueous extracts demonstrate strong free-radical scavenging potential and neuroprotective activity.

Table 1: Biological properties of Evolvulus alsinoides

Parameter	Observation / Value	Remarks / Significance
Family	Convolvulaceae	Commonly known as morning glory family
Major Phytochemicals	Alkaloids, flavonoids, saponins, tannins	Bioactive compounds responsible for medicinal properties
Extract Types	Aqueous, Methanolic, Ethanolic	Used in pharmacological evaluations
Biological Activities	Antioxidant, Nootropic, Anti-inflammatory	Supports traditional Ayurvedic use
Optimal Collection Season	Post-monsoon (Aug–Oct)	Highest phytochemical concentration
Plant Part Used	Whole plant (mainly aerial parts)	Rich in secondary metabolites
Morphology	Herbaceous, blue flowers, slender stems	Typical of genus *Evolvulus*
DPPH Radical Scavenging Activity	~72–85% (ethanolic extract)	Indicates strong antioxidant capacity
Traditional Use	Memory enhancer, stress reliever	Mentioned in Ayurvedic texts like *Charaka Samhita*

4.2. UV-Visible spectroscopy

The formation of CuO–SrO nanocomposites was initially confirmed by UV–Visible spectroscopy. The absorption spectrum exhibited a distinct absorption band in the wavelength range of 270–310 nm, indicating the successful formation of the mixed metal oxide nanocomposite. This absorption is attributed to the charge transfer transition between oxygen (O^{2-}) and the Cu^{2+} and Sr^{2+} ions present in the composite structure. The observed absorption peak confirms the formation of crystalline CuO–SrO nanocomposites with enhanced optical characteristics. The phytochemicals present in the Evolvulus alsinoides extract act as natural reducing and capping agents during synthesis, leading to the formation of uniformly dispersed nanoparticles. The interaction between these phytochemicals and the nanoparticle surface improves optical stability and prevents excessive particle agglomeration. Furthermore, the synergistic interaction between CuO and SrO enhances charge separation and suppresses electron–hole recombination, which is beneficial for photocatalytic and antimicrobial applications. The UV–Visible spectrum therefore confirms the successful synthesis of CuO–SrO nanocomposites with promising optical properties suitable for multifunctional applications. The electronic absorption spectrum of synthesized CuO–SrO nanocomposites is given in **Fig. 1**.

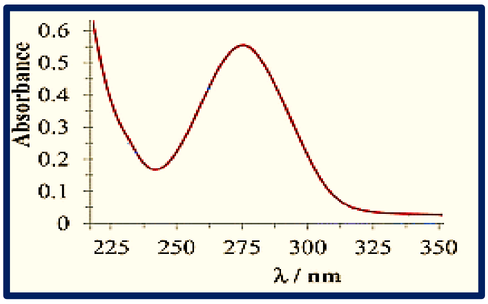


Figure 1 UV-VIS spectrum of CuO–SrO nanocomposites

4.3. Antibacterial Activity

The antibacterial activity of the green-synthesized CuO–SrO nanocomposites was evaluated against three Gram-positive bacteria (Bacillus subtilis, Bacillus cereus, and Staphylococcus albus) and three Gram-negative bacteria (Escherichia coli, Pseudomonas aeruginosa, and Klebsiella pneumoniae) using the disc diffusion method. The synthesized nanocomposites exhibited appreciable antibacterial activity against all tested bacterial strains. Among the tested microorganisms, the highest zone of inhibition was observed against Pseudomonas aeruginosa (22 mm), followed by Staphylococcus albus (21 mm), Klebsiella pneumoniae (20 mm), Bacillus cereus (19 mm), Escherichia coli (18 mm), and Bacillus subtilis (17 mm). These results demonstrate the broad-spectrum antibacterial efficacy of the CuO–SrO nanocomposites against both Gram-positive and Gram-negative bacteria. The enhanced antibacterial activity can be attributed to the synergistic effect of CuO and SrO nanoparticles. The nanocomposites generate reactive oxygen species (ROS), including hydroxyl radicals and superoxide ions, which induce oxidative stress and damage bacterial cell membranes. In addition, the positively charged nanoparticle surface interacts electrostatically with negatively charged bacterial cell walls, increasing membrane permeability and causing leakage of intracellular components. The release of Cu^{2+} ions further interferes with essential cellular enzymes, proteins, and nucleic acids, ultimately resulting in bacterial cell death. The incorporation of SrO improves structural stability and surface reactivity, thereby enhancing the overall antibacterial performance of the nanocomposites. The observed antibacterial results indicate that the green-synthesized CuO–SrO nanocomposites possess significant bactericidal activity and may serve as promising antimicrobial materials for biomedical coatings, wound dressings, water purification, and environmental disinfection (**Fig. 2, Fig. 3,** and **Table 2**).

Table 2. Zone inhibition of CuO–SrO nanocomposites with Bacteria's

S.No.	Bacteria	CuO–SrO nanocomposites	Control (STREPTOMYCIN)
1.	**BS**	17	22
2.	**BC**	19	20
3.	**SA**	21	12
4.	**PA**	22	12
5.	**KP**	20	13
6.	**E.coli**	18	11

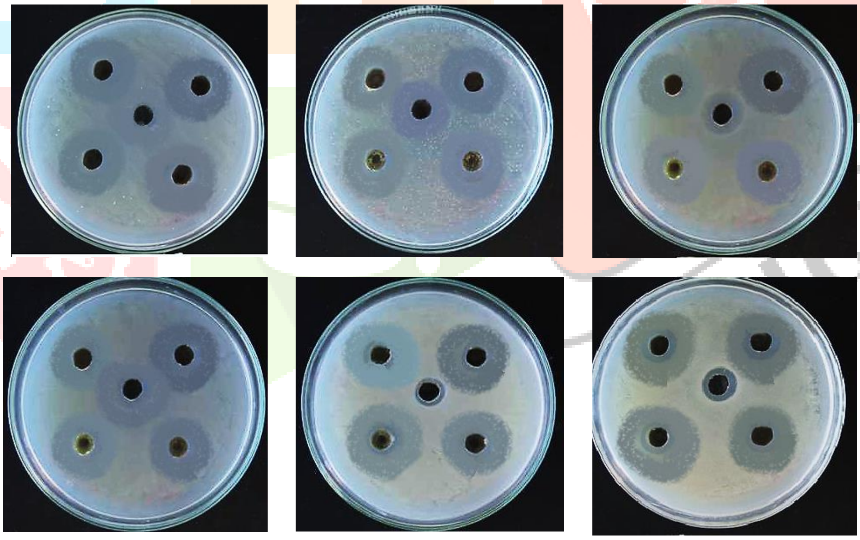


Figure 2. Antibacterial activity of CuO–SrO nanocomposites

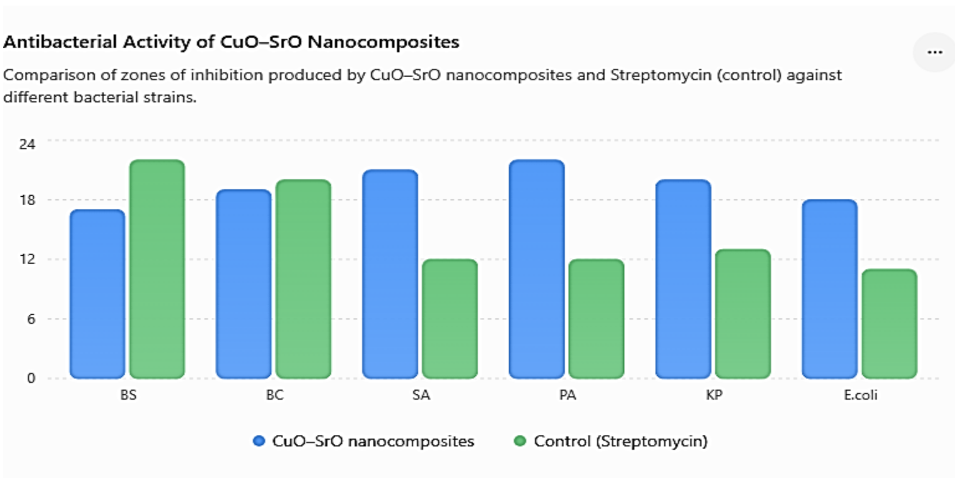


Figure 3. Comparison of the antibacterial activity of green-synthesized CuO–SrO nanocomposites and the Streptomycin control against Gram-positive and Gram-negative bacterial strains.

5. Future scope

The green synthesis of CuO–SrO nanocomposites using Evolvulus alsinoides extract presents significant opportunities for future research and technological applications. Further studies should focus on optimizing synthesis parameters such as precursor concentration, pH, reaction temperature, and calcination conditions to achieve better control over particle size, crystallinity, and morphology. Advanced characterization techniques, including X-ray photoelectron spectroscopy (XPS), transmission electron microscopy (TEM), Raman spectroscopy, and photoluminescence analysis, can provide deeper insights into the surface chemistry, elemental oxidation states, and charge transfer mechanisms of the synthesized nanocomposites. The photocatalytic performance of CuO–SrO nanocomposites can be further explored for the degradation of organic dyes, pharmaceutical contaminants, and industrial wastewater under visible-light irradiation. In addition, evaluating their antioxidant, anticancer, antibiofilm, and cytotoxic properties would broaden their potential biomedical applications. The incorporation of CuO–SrO nanocomposites into polymeric films, wound dressings, coatings, and nanocomposite membranes may also lead to the development of advanced antimicrobial materials for healthcare and environmental protection. Future investigations should emphasize large-scale green synthesis, long-term stability, reusability, and environmental safety to facilitate commercial applications. Overall, Evolvulus alsinoides-mediated CuO–SrO nanocomposites represent a promising class of sustainable multifunctional nanomaterials with considerable potential in environmental remediation, catalysis, energy-related technologies, and biomedical engineering.

6. Conclusions

In the present study, CuO–SrO nanocomposites were successfully synthesized through an eco-friendly green synthesis approach using Evolvulus alsinoides extract as a natural reducing and stabilizing agent. The adopted method eliminated the use of hazardous chemicals and demonstrated a simple, cost-effective, and sustainable route for the preparation of multifunctional metal oxide nanocomposites. The phytochemicals present in the plant extract played a crucial role in facilitating nanoparticle formation while improving their stability and dispersion. The successful formation of CuO–SrO nanocomposites was confirmed by UV–Visible spectroscopy, which exhibited a characteristic absorption band in the 270–310 nm region corresponding to the charge transfer transitions of the mixed metal oxide system. The optical results indicate the formation of stable CuO–SrO nanocomposites with enhanced electronic properties, making them suitable for photocatalytic and biomedical applications. The synthesized nanocomposites exhibited remarkable antibacterial activity against both Gram-positive and Gram-negative bacterial strains. The highest zone of inhibition was observed against Pseudomonas aeruginosa (22 mm) and Staphylococcus albus (21 mm), followed by Klebsiella pneumoniae (20 mm), Bacillus cereus (19 mm), Escherichia coli (18 mm), and Bacillus subtilis (17 mm). The enhanced antibacterial performance is attributed to the synergistic interaction between CuO and SrO, which promotes reactive oxygen species generation, disrupts bacterial cell membranes, and inhibits essential cellular processes. These findings demonstrate that the green-synthesized CuO–SrO nanocomposites possess broad-spectrum antibacterial activity and can serve as effective antimicrobial materials. Overall, this work highlights the potential of Evolvulus alsinoides-mediated green synthesis as a sustainable strategy for producing CuO–SrO nanocomposites with desirable optical and antibacterial properties. The synthesized nanocomposites exhibit significant potential for applications in antimicrobial coatings, water purification, environmental remediation, and other biomedical fields. The outcomes of this study provide a foundation for the development of environmentally benign multifunctional nanomaterials and encourage further exploration of plant-mediated synthesis for advanced technological applications.

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