

Green Fabrication of Ag-Functionalized WO₃ Nanostructures: Advancing Visible-Light Photocatalysis and Biodiesel Production

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In this study, *Asystasia gangetica* leaf extract was employed as a green precursor for the synthesis of silver-functionalized tungsten trioxide nanoparticles (Ag-WO₃ NPs) via the solution combustion method. The synthesized nanoparticles were characterized using X-ray diffraction (XRD), Fourier-transform infrared (FTIR) spectroscopy, UV-visible spectroscopy, and scanning electron microscopy (SEM) to investigate their crystalline structure, functional groups, optical properties and surface morphology, respectively. The visible-light driven photocatalytic performance of Ag-WO₃ NPs was evaluated using crystal violet (CV) as a model dye and an effluent sample collected from a silk-dyeing unit. The results demonstrated 88% degradation of CV within 6 h at pH 9.2 and 85% degradation of the effluent within 8 h at pH 6.8 under visible-light irradiation. The synthesized Ag/WO₃ NPs were tested as transesterification catalysts for converting waste sunflower oil into methyl esters, extending their potential use beyond photocatalysis to wastewater treatment and biodiesel production.

Keywords: Tungsten trioxide, Green synthesis, Crystal violet, Photocatalysis, Effluent, Transesterification.

INTRODUCTION

Water pollution is a major concern as waste, plastics, chemicals and other contaminants enter water bodies. Unsafe water contributes substantially to mortality worldwide [1]. Less than 1% of Earth's freshwater is readily available for human consumption and contamination places further pressure on this limited resource [2]. Population growth is expected to increase demand for safe drinking water, while pollution continues to threaten its availability [3]. Textile dyeing effluents are one source of contamination. The discharge of untreated or inadequately treated wastewater into drainage systems can introduce persistent and toxic colourants into the environment [4,5]. Inefficient treatment practices remain in use at many facilities [6,7].

Sustainable energy technologies are another important part of efforts to reduce environmental pollution. Transesterification converts vegetable oils and animal fats into biodiesel,

offering a renewable alternative to conventional fossil fuels and potentially reducing dependence on petroleum [8,9]. Fuel additives can be used to improve fuel properties, engine performance and combustion efficiency, and to reduce emissions [10]. These approaches contribute to the development of cleaner energy systems and support efforts to limit climate change [11].

Semiconductor-based photocatalysis has attracted considerable attention as a means of addressing limitations in the conventional water-treatment methods [12]. Materials investigated as photocatalysts include transition-metal oxide nanoparticles [13-15], metal nanoparticles [16,17], metal-doped metal oxides [18,19], metal sulphides [20] and ternary composites [21-25]. Their applications extend to sensing [26-28], optical devices [29,30], electrical systems [31,32] and magnetic materials [33,34]. Transition-metal oxide nanoparticles have also been studied as heterogeneous catalysts for transesterification reactions involved in biodiesel and fuel-additive production.

WO₃ nanoparticles have been widely investigated for the visible-light driven degradation of organic pollutants, such as dyes and pesticides. Their ability to absorb sunlight and generate reactive oxygen species (ROS) can support the breakdown of contaminants in water and air [35,36]. WO₃ has also been explored for energy-storage systems, smart-window technologies [37], hydrogen production, catalysis [38], and sensing and detection [39]. Modifying catalytic materials with metals or metal oxides is one strategy used to alter their photocatalytic properties and catalytic performance [40-43].

Silver (Ag) was selected as a dopant for WO₃ in this study, as it may promote charge separation and suppress electron-hole recombination, thereby improving photocatalytic activity [25-28]. Plant and fruit extracts have been used in green nanoparticle synthesis, offering alternatives to conventional synthesis routes [29-31]. This work aims to synthesize Ag/WO₃ nanoparticles using an economical solution-combustion method, with an aqueous extract of *Asystasia gangetica* leaves serving as the fuel. The nanoparticles will be investigated for the photocatalytic degradation of crystal violet (CV) dye and dyeing-effluent samples under different light sources. The effects of irradiation time, dye concentration or effluent volume, photocatalyst dosage and pH on degradation performance will be examined.

EXPERIMENTAL

Analytical-grade crystal violet (Sigma-Aldrich), sodium tungstate (Na₂WO₄) and silver nitrate (AgNO₃) were procured from a local supplier and used without further purification. Distilled water was used throughout the experimental procedures. Borosilicate glassware was used for all experiments. The pH of the effluent samples was measured using a Systronics pH meter (India).

Collection of effluent samples: Effluent samples were collected from silk dyeing units in Tiptur, India. The samples were filtered sequentially through standard filter paper and Whatman filter paper, followed by centrifugation at 1200 rpm for 20 min. The resulting effluent, with a measured pH of 6.8, was used for the degradation studies.

Collection of discarded sunflower oil: Used sunflower oil was collected from local sources, heated thoroughly to remove residual moisture and stored in an airtight container until further use in the experiments.

Preparation of extract of *A. gangetica* leaves: Leaves of *Asystasia gangetica* (coromandel) were collected from Hebbakavadi hamlet, Mandya District, India. The leaves were washed with distilled water and sun-dried for two days, followed by oven-drying at 80 °C for 48 h. The dried leaves were then ground into a fine powder. Approximately 30 g of the leaf powder was heated in 200 mL of distilled water until the volume was reduced to 25 mL. The resulting mixture was filtered, and the filtrate and filtered material were used in the preparation of WO₃ and Ag/WO₃ nanoparticles.

Synthesis of WO₃ and Ag/WO₃ nanoparticles using *A. gangetica* leaves extract

Optimization of extract of *A. gangetica* leaves: WO₃ nanoparticles were synthesized using a green synthesis approach.

Four precursor solutions were prepared by dissolving 2.1814 g of sodium tungstate in a minimum amount of distilled water. *A. gangetica* leaf extract was added to the solutions in volumes of 1.5, 2.0, 2.5 and 3.0 mL, respectively, to serve as a stabilising and reducing agent. The mixtures were continuously stirred at 40 °C for approximately 30 min. The resulting gel-like materials were transferred to silica crucibles and calcined in a muffle furnace at 650 °C for 3 h. No product was obtained using 1.5 or 2.0 mL of the leaf extract, whereas product formation was achieved with 2.5 and 3.0 mL. A volume of 2.5 mL was selected for the synthesis of WO₃ nanoparticles.

For the synthesis of 1 wt.% Ag-doped WO₃ nanoparticles, 2.1814 g of sodium tungstate and 0.0121 g of AgNO₃ were dissolved in a minimum amount of distilled water to prepare three separate solutions. *A. gangetica* leaf extract was then added in volumes of 4, 6 and 8 mL, respectively. The mixtures were continuously stirred at 40 °C for approximately 30 min. The resulting gel-like materials were transferred to silica crucibles and calcined at 650 °C for 3 h in a muffle furnace. The product formation was not observed with 4 or 6 mL of the extract; therefore, 8 mL of *A. gangetica* leaf extract was used to synthesize Ag/WO₃ nanoparticles.

Phytochemical screening: Phytochemical screening of *A. gangetica* leaf extract was performed to identify flavonoids, alkaloids, phenolic compounds, saponins, tannins, sugars and amino acids [44]. Flavonoids were detected using the alkaline reagent test, in which 2 mL of leaf extract was treated with 8 mL of 2 N NaOH; the appearance of a yellow colour indicated their presence. Alkaloids were assessed using Wagner's test by adding 2 mL of HCl and 1 mL of Wagner's reagent to 2 mL of extract, with a yellow precipitate confirming their presence. Phenolic compounds and tannins were identified using the FeCl₃ test, in which the addition of 2 mL of neutral FeCl₃ solution to 2 mL of extract resulted in a dark-blue colour. Saponins were screened by diluting 2 mL of extract to 50 mL with distilled water and vigorously shaking the mixture in a BOD bottle for 15 min; the formation of approximately 1 cm of foam indicated their presence. Sugars were tested using Benedict's reagent: 5 mL of the reagent was mixed with eight drops of extract and heated for 5 min, with a reddish-brown precipitate indicating a positive result. Amino acids were detected by adding a few drops of 2% ninhydrin solution to 2 mL of extract diluted to 10 mL, followed by heating in a water bath for 5 min; the development of a deep-blue colour indicated their presence.

Experimental setup for photocatalysis: The experimental setup consisted of a 250 mL glass vessel, a 40 W visible-light bulb, a magnetic stir bar and a Remi magnetic stirrer operated at 450 rpm. For CV dye degradation, 100 mL dye solutions with concentrations of 3, 6, 9 and 12 ppm were treated with 8, 12, 16 and 20 mg of Ag/WO₃ NPs, respectively. For effluent degradation studies, 100 mL solutions containing 25, 50, 75 and 100 mL of effluent were treated with 8, 16, 24 and 32 mg of Ag/WO₃ NPs, respectively. Before irradiation, the solutions were aerated in the dark for 30 min. They were then continuously stirred under visible light. Approximately 3 mL aliquots were withdrawn every 30 min and centrifuged and the supernatants were analysed using a UV-visible spectrophotometer (Labman, LMSP-UV1900).

RESULTS AND DISCUSSION

Powder XRD analysis: The XRD pattern of the Ag/WO₃ composite exhibits well-defined diffraction peaks at $2\theta = 16.68^\circ, 27.59^\circ, 32.56^\circ, 48.76^\circ, 51.97^\circ$ and 56.94° , which are indexed to the monoclinic WO₃ phase (Fig. 1) in accordance with JCPDS card No. 43-1035 [45]. The additional peaks at $2\theta = 43.08^\circ, 64.48^\circ$ and 78.51° are assigned to metallic Ag (Ag⁰), consistent with JCPDS card No. 04-0783 [44]. The presence of both sets of reflections supports the coexistence of crystalline WO₃ and metallic Ag in the composite. The average crystallite size, estimated using the Debye–Scherrer equation, was approximately 18 nm, confirming the nano-scale crystalline nature of the synthesized Ag/WO₃ material.

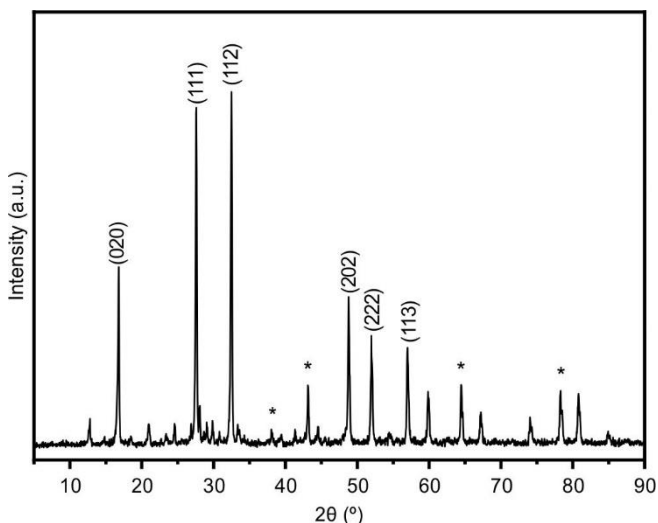


Fig. 1. XRD pattern of as-synthesized Ag/WO₃ NPs

UV-visible spectral analysis: The UV visible absorption spectra of WO₃ and Ag/WO₃ nanocomposites are shown in Fig. 2a-b. The pristine WO₃ exhibits a strong absorption peak at approximately 312 nm, which is attributed to the intrinsic charge- transfer transition from O 2p orbitals to W

5d orbitals. After the incorporation of Ag nanoparticles, the absorption peak is slightly shifted to 305 nm, which indicate a modification in the electronic environment of WO₃ due to the interaction between Ag and WO₃. Moreover, the Ag/WO₃ nanocomposite displays an additional broad absorption band centered at around 416 nm, which is characteristic of surface plasmon resonance (SPR) of Ag nanoparticle. The presence of these SPR band confirms the successful deposition of Ag onto the WO₃ surface [46-48]. Compared with pristine WO₃, the Ag/WO₃ nanocomposite exhibits stronger absorption in the visible-light region, which may be attributed to the contribution of Ag nanoparticles to its optical response. These spectral features support the formation of the Ag/WO₃ nanocomposite and indicate that Ag incorporation alters the optical properties of WO₃.

FTIR analysis: To determine the main functional groups in the leaf extract and their potential role in the synthesis and stabilization of Ag/WO₃ NPs, FTIR studies were performed. Fig. 3a displays the FTIR spectrum of the extract from *A. gangetica* leaves. The FTIR spectrum of the *A. gangetica* leaf extract exhibits absorption peaks at 2926 and 2856 cm⁻¹, assigned to C–H stretching vibrations, and at 3608 and 3740 cm⁻¹, attributed to O–H stretching [29]. The peak at 1739 cm⁻¹ corresponds to C–O stretching, while those at 667 and 1463 cm⁻¹ are associated with asymmetric NH₂ rocking and C–H vibrations, respectively. These functional groups may participate in the reduction of silver ions and act as capping agents during the formation of Ag/WO₃ NPs [30,49]. The FTIR spectrum of Ag/WO₃ NPs (Fig. 3b) displays a prominent band at 553 cm⁻¹, attributed to W–O stretching vibrations, and a peak at 816 cm⁻¹ assigned to the W–O–W bridging mode [50]. The absorption band at 1105 cm⁻¹ is associated with C–O groups, while the peaks at 2950 and 1400 cm⁻¹ correspond to C–H stretching and bending vibrations, respectively. The bands at 3444 and 1630 cm⁻¹ are attributed to the O–H stretching and H–O–H bending vibrations of adsorbed water molecules. These additional bands may arise from phytochemical residues associated with the aqueous leaf extract used during Ag/WO₃ synthesis [30].

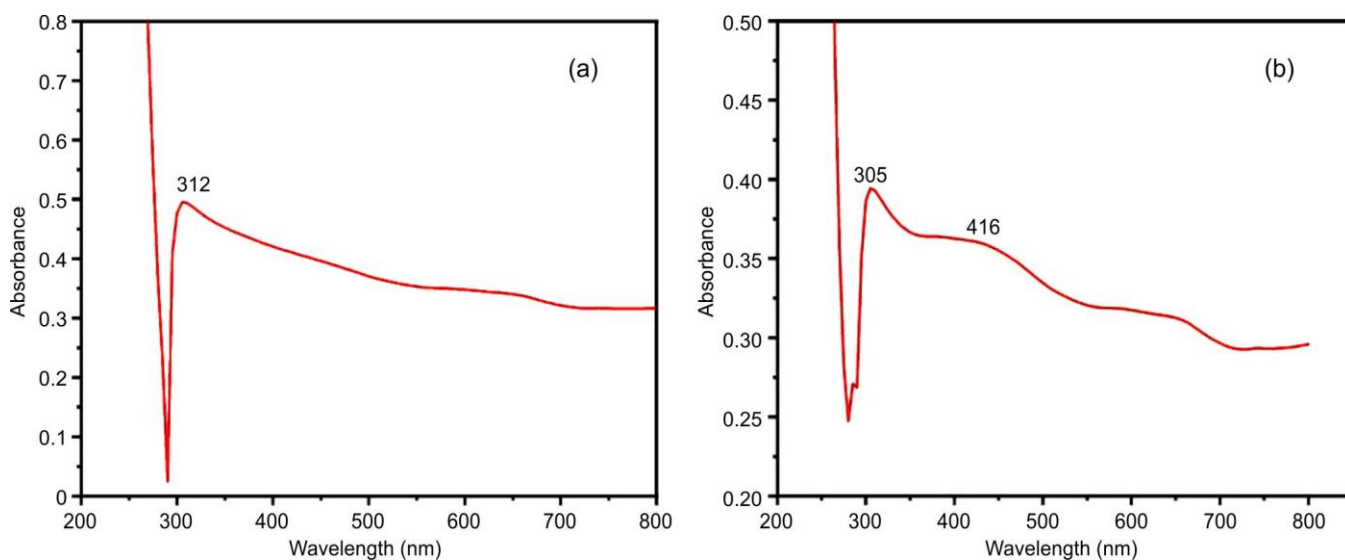


Fig. 2. UV-Vis spectra of (a) WO₃ and (b) Ag/WO₃ NPs

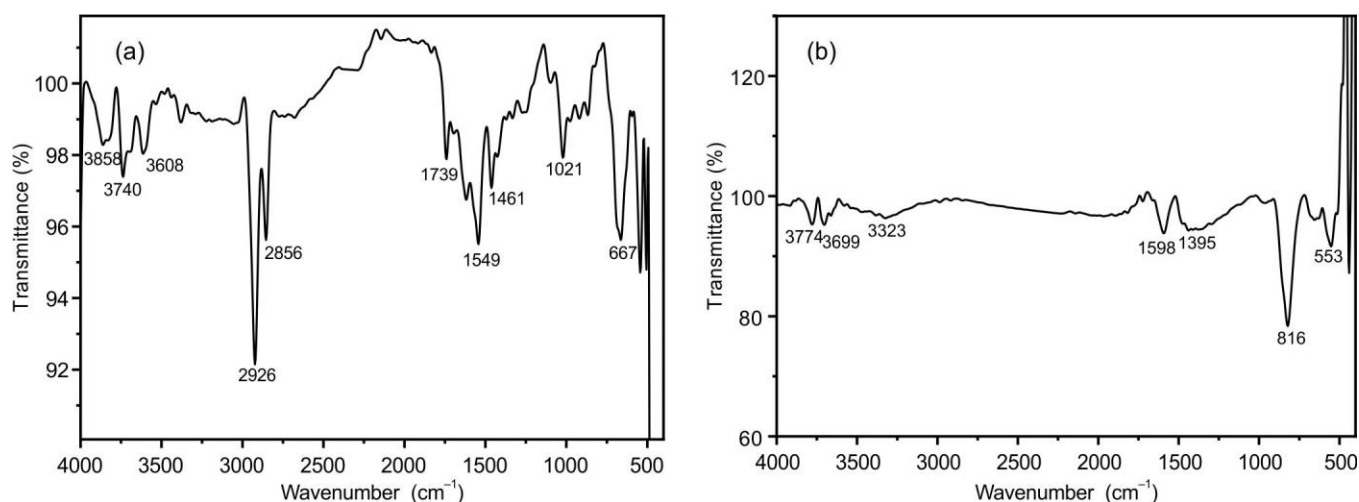


Fig. 3. FTIR spectra of (a) *A. gangetica* leaves extract and (b) Ag/WO₃ NPs

SEM-EDAX analysis: Fig. 4 presents the SEM images of the synthesized Ag/WO₃ NPs, revealing a porous structure with an irregular morphology. The presence of pores and voids, together with variations in particle shape, influences the

material's surface characteristics and may affect its permeability, adsorption capacity and mechanical properties. The elemental composition of the Ag/WO₃ nanocomposite was examined by EDX spectroscopy (Fig. 4c). The spectra confirm

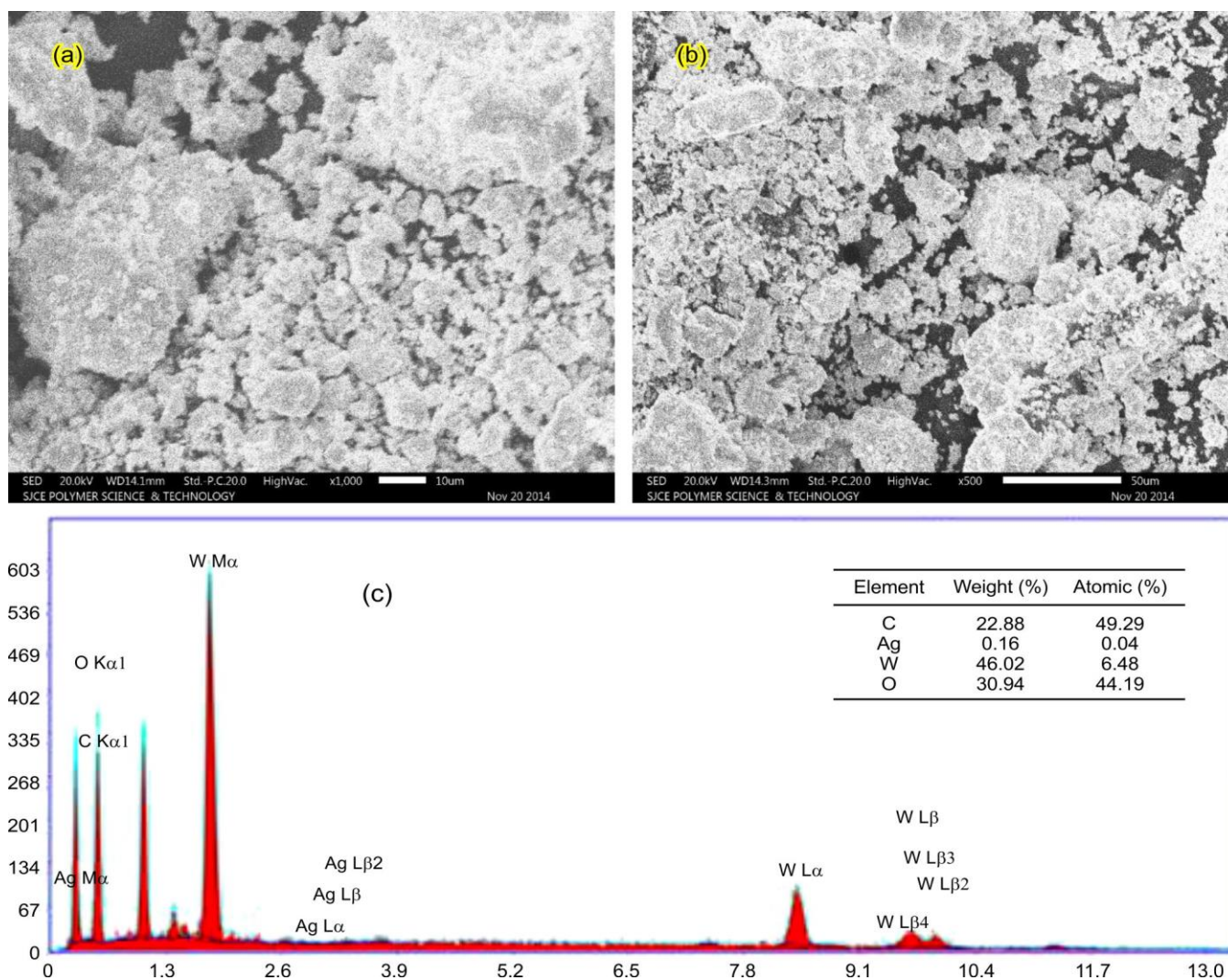


Fig. 4. SEM images of synthesized (a,b) Ag/WO₃ NPs and (c) EDAX spectrum of the synthesized Ag/WO₃ NPs

the presence of Ag, W and O, consistent with the expected elemental composition of the composite. The elemental percentages listed in the inset table agree with the precursor ratios used during synthesis.

Photocatalytic activity: The primary objective of this study was to investigate the visible-light driven photocatalytic degradation of hazardous dye effluent using the synthesized Ag/WO₃ NPs. Industrial dyeing processes release coloured wastewater containing potentially harmful pollutants, making effective treatment essential. The photocatalytic activity of Ag/WO₃ NPs was evaluated under different experimental conditions to identify the effects of key operating parameters. Photocatalytic performance depends on factors such as light absorption, charge-carrier generation and recombination, and the formation of reactive species, including hydroxyl radicals [35,36]. Upon irradiation, the photocatalyst generates electron-hole pairs. These charge carriers may participate in surface reactions or recombine, reducing photocatalytic efficiency. Their separation and migration to active surface sites can promote the formation of reactive oxygen species, including hydroxyl ($\cdot\text{OH}$) and hydroperoxyl ($\cdot\text{HO}_2$) radicals, which contribute to pollutant degradation. The increased surface area of metal oxide nanoparticles may provide additional active sites for charge-carrier reactions [12]. The synthesized material exhibited a band-gap energy of 2.22 eV, estimated from the Tauc plot, suggesting its ability to absorb visible light [13]. The effects of light source, photocatalyst dosage, dye concentration, pH and irradiation time were investigated using crystal violet (CV) dye and dyeing-effluent samples as model pollutants. Initial and final pollutant concentrations (C_i & C_f) were determined from UV-visible absorption spectra and the degradation percentage was calculated using eqn. 1:

$$\text{Degradation (\%)} = \frac{C_i - C_f}{C_i} \times 100 \quad (1)$$

Influence of light source on dye decomposition: The UV-visible absorption spectrum confirms that the synthesized Ag/WO₃ NPs are optically active in the visible-light region. Their photocatalytic performance was evaluated under different

light sources while maintaining the same experimental conditions. As shown in Fig. 5a, no appreciable degradation of CV dye or the effluent sample occurred in the absence of light. The degradation rates under UV irradiation were considerably lower than those observed under visible-light irradiation. Under visible light, Ag/WO₃ NPs effectively degraded 88% of CV within 6 h and 85% of the effluent sample within 8 h (Fig. 5b). Based on these results, visible light was selected for the subsequent investigation of the photocatalytic performance of Ag/WO₃ NPs.

Effect of catalyst dosage: In this study, the Ag/WO₃ NPs dosage was varied from 8 to 20 mg under visible-light irradiation, while maintaining the pH at 7, the effluent volume at 6 mL and the CV concentration at 9 ppm (Fig. 6a). The degradation efficiency increased with catalyst loading up to an optimum level, owing to the availability of more active sites for reactive species generation. Beyond this level, excess catalyst may promote particle aggregation and light scattering, reducing the number of accessible active sites and limiting photocatalytic performance. As shown in Fig. 6b, the optimum Ag/WO₃ NPs dosages were 16 mg for CV degradation and 24 mg for effluent degradation. These respective dosages were selected for the subsequent optimization experiments involving the other reaction parameters.

Influence of dye concentration: The effect of pollutant concentration on photocatalytic degradation was investigated by varying the CV concentration from 3 to 12 ppm under UV irradiation, while maintaining the Ag/WO₃ NP dosage at 16 mg and the solution pH at 7. For the effluent sample, whose dye concentration was unknown, the volume was varied from 3 to 12 mL under the same catalyst dosage and pH conditions. The results are presented in Fig. 7. The degradation efficiency decreased as the CV concentration increased, falling from 93% to 62% as the concentration rose from 3 to 12 ppm. A similar trend was observed for the effluent, with removal efficiency declining from 97% to 73% as the effluent volume increased. The higher degradation efficiencies at lower pollutant concentrations may be attributed to reduced competition for active sites and improved light penetration through the

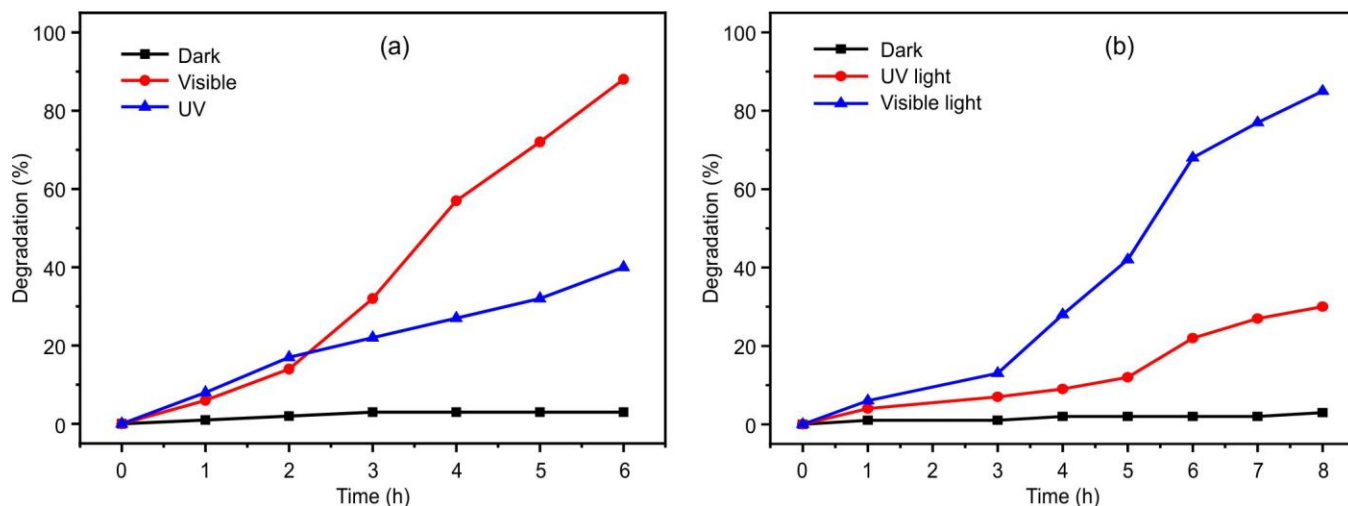


Fig. 5. Effect of light source on photo-catalytic degradation of (a) CV with Ag/WO₃ NPs and (b) effluent sample with Ag/WO₃ NPs (Conditions: CV concentration = 6 ppm, photocatalyst amount = 12 mg and pH of solution = 7 for effluent volume = 75 mL, catalyst = 24 mg, pH 7)

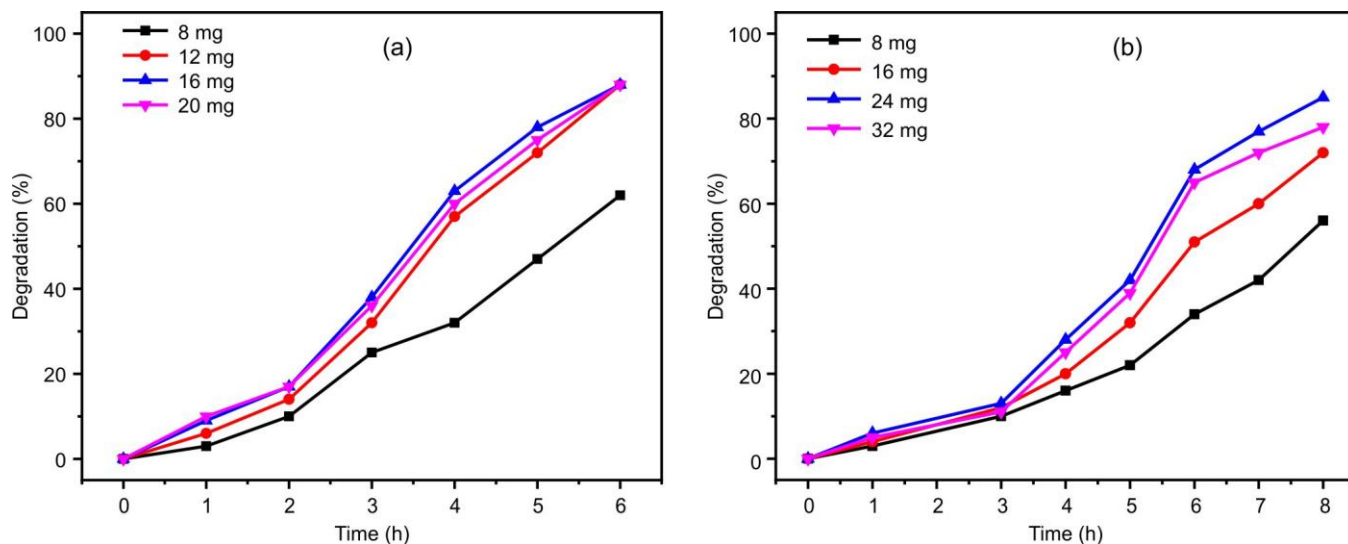


Fig. 6. Effect of catalyst concentration on photo-catalytic degradation of (a) CV with Ag/WO₃ NPs and (b) effluent sample with Ag/WO₃ NPs (Conditions: CV concentration = 6.0 ppm, photocatalyst amount = 16.0 mg and pH of solution = 7, for effluent sample volume = 75 mL, photocatalyst amount = 24.0 mg)

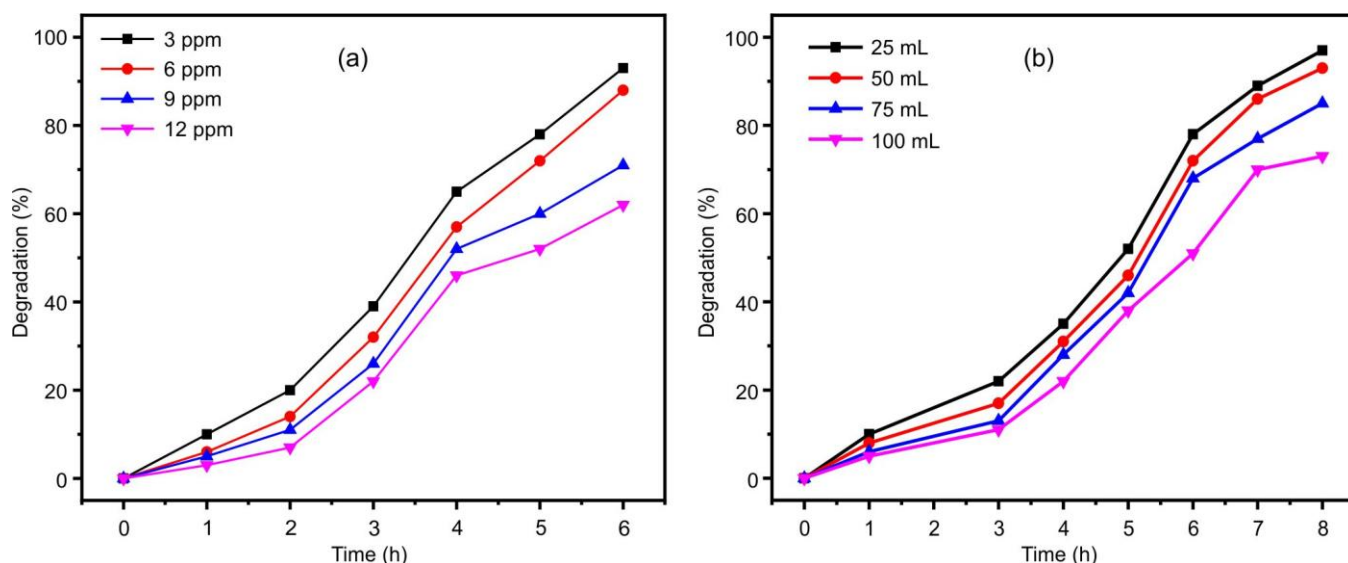


Fig. 7. Effect of dye concentration on photo-catalytic degradation of (a) CV with Ag/WO₃ NPs and (b) effluent sample with Ag/WO₃ NPs (Conditions: photocatalyst amount = 16.0 mg and pH of solution = 7, for effluent sample, photocatalyst amount = 24.0 mg, pH of solution = 6.87)

solution. At higher concentrations, greater surface coverage by dye molecules may block active sites, while increased light absorption and scattering by the pollutant can limit the light reaching the photocatalyst. Based on these findings, CV at 6 ppm and an effluent volume of 6 mL were selected for subsequent optimization studies.

Influence of pH: Solution pH is an important factor influencing the photocatalytic degradation of organic dyes, as it can affect surface charge and the formation of reactive species, including hydroxyl radicals ($\cdot\text{OH}$). The effect of pH on the degradation of CV dye and the effluent sample using Ag/WO₃ NPs was investigated at pH 4.0, 7.0 and 9.2 under visible-light irradiation, while keeping the other experimental conditions constant. CV degradation was studied using 6 ppm dye and 16 mg of catalyst, whereas the effluent experiments

used 75 mL of effluent and 24 mg of catalyst. As shown in Fig. 8, the lowest degradation efficiencies were recorded at pH 4.0, with 41% of CV degraded within 6 h and 46% of the effluent removed within 8 h. The degradation efficiency increased with pH, reaching 88% for CV and 85% for the effluent at pH 7.0, and 99% and 98%, respectively, at pH 9.2. This improvement under alkaline conditions may be associated with changes in the surface charge of photocatalyst material and enhanced availability of hydroxyl radicals, which can promote the degradation process. For the effluent treatment experiments, the pH was not adjusted, as the aim was to evaluate photocatalytic degradation under the original conditions of effluent.

Photocatalytic mechanism: A possible mechanism for the enhanced photocatalytic activity of Ag/WO₃ NPs is pro-

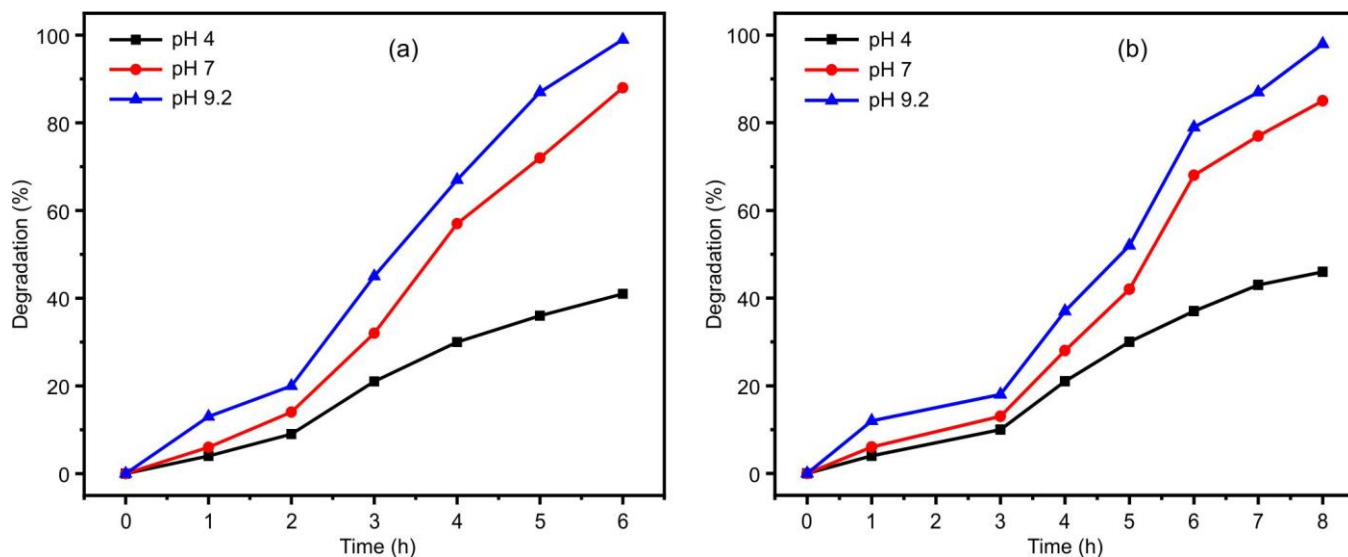
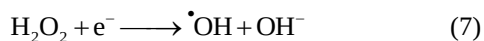
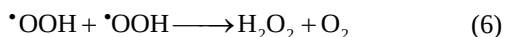
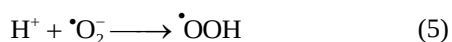
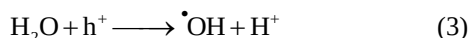
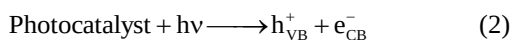


Fig. 8. Effect of pH on photo-catalytic degradation of (a) CV with Ag/WO₃ NPs and (b) effluent sample with Ag/WO₃ NPs (Conditions: CV concentration = 6.0 ppm, photocatalyst amount = 16.0 mg)

posed based on the work functions of Ag and WO₃, reported as 4.26 and 5.7 eV, respectively. Upon contact, electrons may transfer from Ag to WO₃ until their Fermi levels equilibrate, resulting in charge redistribution and band bending at the interface. Under irradiation, photogenerated electrons in WO₃ may then migrate to the Ag nanoparticles, reducing electron-hole recombination and improving charge separation. Although the conduction-band (CB) potential of WO₃ is more positive than the one-electron reduction potential of O₂, oxygen reduction through multielectron pathways may occur, leading to the formation of H₂O₂ [44]. Under visible-light irradiation, electrons are excited from the valence band (VB) to the CB, generating electron-hole pairs in WO₃. Some electrons may be trapped at oxygen-vacancy defects, while the remaining charge carriers participate in surface reactions. Electrons can react with dissolved oxygen to form reactive oxygen species, while holes may oxidize surface hydroxide ions or water to generate hydroxyl radicals ([•]OH). These reactive species can attack CV molecules and promote their degradation. H₂O₂ may further contribute to the process by generating additional [•]OH radicals through electron transfer reactions. The proposed pathway ultimately involves the breakdown of the dye into simpler products, potentially including carbon dioxide and water.



According to these equations the photo-decomposition of dye is accomplished over the Ag/WO₃ NPs photocatalyst.

Leaching test: A leaching test was performed to assess whether the photocatalytic degradation of CV was dependent on the presence of Ag/WO₃ NPs in the reaction mixture. The experiment was conducted at pH 7 using 6.0 ppm CV and 16.0 mg of photocatalyst. After 3 h of irradiation under the established conditions, the catalyst was removed by flotation, and the remaining solution was stirred for a further 3 h. As shown by the red curve in Fig. 9, no further degradation occurred after catalyst removal. This result suggests that the continued degradation of CV requires the presence of the Ag/WO₃ photocatalyst under the conditions tested.

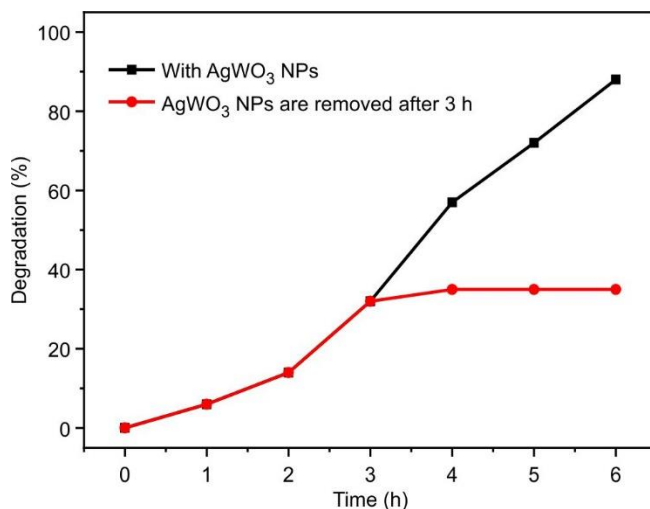


Fig. 9. Leaching test of Ag/WO₃ NPs during the photocatalytic degradation of CV dye under optimized conditions (CV = 6.0 ppm, catalyst = 16.0 mg, pH = 7)

Stability and recyclability test: Catalyst stability is an important consideration for practical applications. The photostability and reusability of the synthesized Ag/WO₃ NPs were evaluated through repeated photocatalytic degradation of

aqueous CV solution. After each reaction, the catalyst was recovered by filtration using ashless Whatman filter paper, washed with distilled water and calcined to remove residual dye and reaction products before reuse. The regenerated catalyst, weighing approximately 14.4 mg, was tested under visible light irradiation using 6 ppm CV at pH 7. The recyclability test was performed over three cycles. As shown in Fig. 10, a slight decrease in photocatalytic activity was observed during the first reuse, followed by a more pronounced decline during the second reuse. FTIR spectra of the as-synthesized and regenerated Ag/WO₃ NPs were compared to examine possible structural changes after CV degradation. The spectra showed no substantial changes in the characteristic bands, suggesting that the chemical structure of catalyst remained largely unchanged after use. The catalyst was regenerated by calcination at 500 °C to remove deposited impurities from its surface. Repeatability tests conducted under similar conditions showed consistent CV degradation performance under visible light irradiation, as shown in Fig. 11 [22].

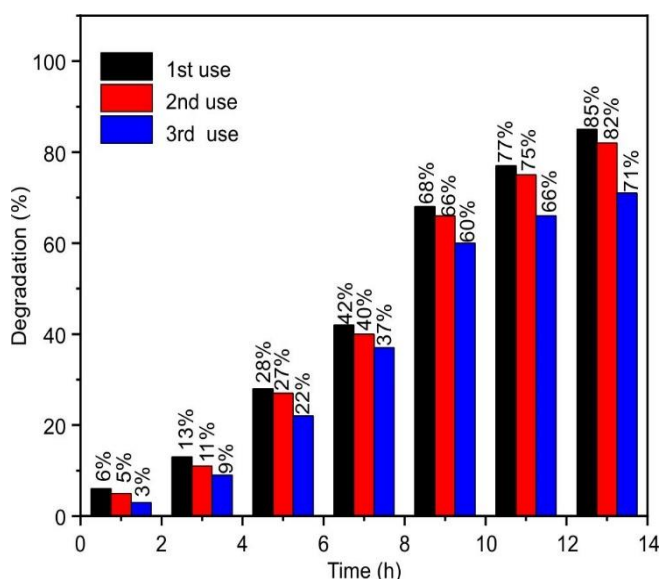


Fig. 10. Reusability performance of Ag/WO₃ NPs in the photocatalytic degradation of CV dye using 16 mg catalyst at pH 7

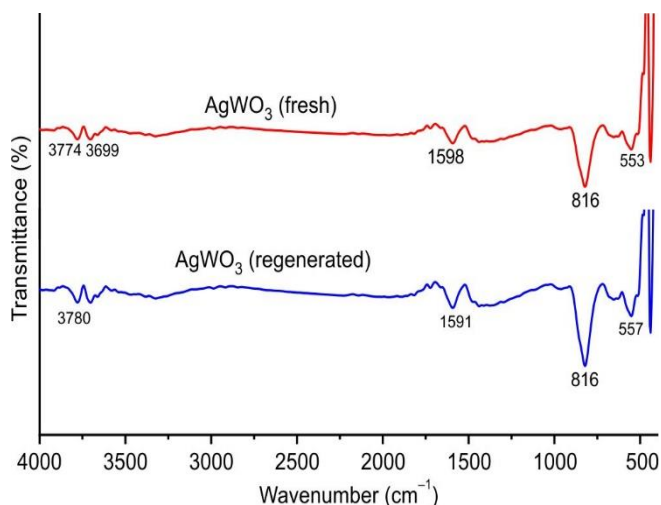


Fig. 11. FTIR spectra of as-synthesized (fresh) and (regenerated) Ag/WO₃ NPs photocatalyst after photodegradation

Transesterification: Conversion of DSFO to DFOME:

The alcohol-to-oil molar ratio is an important factor affecting transesterification efficiency, methyl ester yield and production costs. Since transesterification is reversible and the stoichiometric alcohol-to-oil molar ratio is 3:1, excess methanol is generally required to promote the reaction towards completion and improve contact between methanol and triglycerides. The conversion process is influenced by several parameters, including catalyst loading, alcohol-to-oil ratio, reaction temperature and time, water content and the free fatty acid content of the oil. In this study, the effects of reaction temperature, methanol volume and Ag/WO₃ catalyst dosage on the conversion of discarded sunflower oil (DSFO) into methyl esters (DFOME) were investigated (Table-1).

TABLE-1
OPTIMIZED CONDITIONS FOR THE
PREPARATION OF DFOME

Conditions	Variation	Yield (%)
Temperature (°C)		
Ag/WO ₃ 175 mg;	57	70.2
Methanol 150 mL;	62	98.7
Time 90 min	67	91.7
Methanol (mL)		
Ag/WO ₃ 175 mg;	100	81.2
Temperature 62 °C;	130	92.6
Time 90 min	160	98.7
Ag/WO ₃ (mg)		
Methanol 150 mL;	100	85.6
Temperature 62 °C;	140	98.7
Time 90 min	160	99.1

The reaction temperature was varied between 57, 62 and 67 °C, with continuous stirring for 100 min. The highest reported conversion, 98.7%, was obtained at 62 °C, which was selected for further experiments. Methanol volume was then varied while maintaining the catalyst loading and temperature. The highest reported biodiesel yield of 98.7% was achieved using 140 mL of methanol and this volume was selected for subsequent studies. Catalyst loading was examined at 100, 140 and 160 mg. The amount of transesterification product increased with catalyst loading up to 140 mg, while increasing the dosage to 160 mg did not provide a significant further improvement. Accordingly, 140 mg of Ag/WO₃ NPs, 140 mL of methanol and a reaction temperature of 62 °C were selected as the optimum conditions for transesterification of 1 L of discarded sunflower oil. These parameters were used for the subsequent yield studies.

Conclusion

In conclusion, Ag functionalized WO₃ nanoparticles were successfully synthesized using *Asystasia gangetica* leaf extract through a straightforward combustion process. Their structural, optical and morphological properties were examined using XRD, UV-Vis, FTIR, SEM and EDX analyses. The synthesized material was identified as Ag/WO₃ nanoparticles, and its photocatalytic activity was evaluated for the degradation of crystal violet (CV) dye and pollutants in industrial wastewater. The nanoparticles also exhibited catalytic activity in the transesterification of discarded sun-

flower oil into methyl esters. These findings indicate the potential of the synthesized Ag/WO₃ nanoparticles for both photocatalytic wastewater treatment and biodiesel production.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language and no data, results or scientific conclusions were generated by AI. All analyses, interpretations and conclusions are the authors' own. The authors reviewed and edited the content and take full responsibility for the published work.

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