

***SARGASSUM TENERRIMUM* SEAWEED-MEDIATED GREEN SYNTHESIS OF TERNARY SW/AG-ZNO NANOCOMPOSITES FOR ENHANCED PHOTOCATALYTIC DEGRADATION OF METHYLENE BLUE AND REACTIVE BLUE 198 DYES**

¹Dr V Parthiban, ²Dr S Sheik Mydeen, ³Dr J Jinikamal Eastro, ⁴Dr S Jayasankari, ⁵Dr J Jude Brillin, ⁶Dr M Kadhar Mohidheen, ⁷Mr K Balamurugan, ⁸Mr M Sivakumar

¹PG and Research Department of Chemistry, Kamaraj College (Autonomous), Thoothukudi-628003, Affiliated to Manonmaniam Sundaranar University, Tirunelveli-627012, Tamil Nadu, India.

²Department of Chemistry, Sethu Institute of Technology, Pulloor, Kariapatti, Virudhunagar Dt, 626115, Tamil Nadu, India.

³Department of Physics (S&H) Grace College of Engineering, Thoothukudi-628005, Tamil Nadu, India.

⁴PG Department of Physics V.O.Chidambaram College, Thoothukudi-628008, Tamil Nadu, India.

⁵Department of Physics (S&H) DMI Engineering College Aralvaimozhi-629301, Tamil Nadu, India.

⁶Department of Chemistry (S&H), S.Veerassamy Chettiar College of Engineering and Technology, SVC Nagar, Puliangudi-627855, Tenkasi District, Tamil Nadu, India.

⁷Department of Chemistry (S&H), Infant Jesus College of Engineering, Keelavallanadu-628851, Tuticorin district.

⁸Department of Chemistry (S&H), Nellai College of Engineering, Maruthakulam-627151, Tirunelveli, Tamil Nadu, India.

Received : 07/08 /2026

Accepted :20/09/2026

Published: 09/10/2026

ABSTRACT

The accumulation of recalcitrant synthetic dyestuffs in aquatic ecosystems poses a severe threat to environmental sustainability and human health. This study reports the eco-friendly green synthesis of novel ternary nanocomposites comprising *Sargassum tenerrimum* seaweed biomatrix integrated with silver and zinc oxide nanoparticles (SW/Ag-ZnO NCs). Biosynthesis was driven by bioactive phytochemicals extracted from *Sargassum tenerrimum*, which functioned as natural reducing, capping, and stabilizing agents. Comparative evaluations were conducted across single, binary, and ternary compositions, including seaweed-supported silver nanoparticles (SW-Ag), seaweed-supported zinc oxide nanoparticles (SW-ZnO), silver-zinc oxide nanocomposites (Ag-ZnO), and the fully integrated ternary composite (SW/Ag-ZnO). Optical absorption spectroscopy revealed surface plasmon resonance (SPR) characteristic of Ag nanoparticles alongside shifted excitonic transitions in the ternary matrix. Optical band gap analysis using Tauc plots confirmed a reduction in energy band gap down to 2.5eV–3.0 eV for the heterostructure, facilitating efficient visible-light absorption. Fourier-transform infrared spectroscopy (FT-IR) confirmed functional group participating moieties (hydroxyl, carbonyl, carboxyl, and amine groups) originating from algal polysaccharides and proteins involved in metal ion coordination and lattice stabilization. X-ray diffraction (XRD) patterns verified the co-existence of face-centered cubic Ag and hexagonal wurtzite ZnO crystalline phases within the composite matrix. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) with selected area electron diffraction (SAED) confirmed the formation of highly dispersed, spherical to quasi-spherical nanoparticles anchored onto the biopolymer support. Thermogravimetric analysis (TGA) demonstrated superior thermal stability of the ternary composite, displaying distinct weight-loss stages corresponding to moisture release, biomatrix decomposition, and structural phase stabilization. Brunauer-Emmett-Teller (BET) analysis revealed a Type IV isotherm with H3-type hysteresis, indicating a porous mesoporous framework with enhanced specific surface area (>35 m²/g) and pore volume. Photodegradation kinetics were evaluated under irradiation against target organic pollutants: cationic Methylene Blue (MB) and anionic Reactive Blue 198 (RB 198) dyes. The ternary SW/Ag-ZnO nanocomposite exhibited exceptional photocatalytic efficiency, achieving over 97.2 % degradation for MB and 99.1 % for RB 198 within 150min, vastly outperforming individual components (SW-Ag, SW-ZnO) and binary systems (Ag-ZnO). Kinetic modeling verified pseudo-first-order degradation behaviour, where rate constants (k) were drastically enhanced due to synergistic charge transfer, plasmonic hot electron injection from Ag SPR, and reduced electron-hole recombination mediated by the integrated *Sargassum tenerrimum* biopolymer scaffold.

KEYWORDS: *Sargassum tenerrimum*; Green Synthesis; Ag-ZnO Nanocomposite; Surface Plasmon Resonance; Photocatalytic Degradation; Methylene Blue; Reactive Blue 198; Heterojunction Charge Transfer.

1. INTRODUCTION

Industrial expansion and rapid urbanization have resulted in the increased discharge of synthetic organic dyes into aquatic environments. Industries such as textile manufacturing, printing, paper production, cosmetics, and pharmaceuticals generate dye-containing effluents that pose substantial threats to surface water and groundwater quality. Synthetic dyes, particularly azo dyes and thiazine dyes such as Reactive Blue 198 (RB 198) and Methylene

Blue (MB), are characterized by complex molecular structures, high chemical stability, and resistance to biodegradation and natural photolysis. Their uncontrolled release into aquatic ecosystems reduces light penetration, inhibits photosynthetic activity, disrupts dissolved oxygen balance, and may adversely affect aquatic organisms. Furthermore, certain dyes and their transformation products have been associated with mutagenic, carcinogenic, and cytotoxic effects, highlighting the need for efficient treatment technologies for dye-contaminated wastewater [13, 15, 20, 23].

Conventional wastewater treatment techniques, including adsorption, coagulation–flocculation, membrane filtration, and biological treatment, have been widely employed for dye removal. However, these processes have inherent limitations. Adsorption and coagulation primarily transfer contaminants into another phase, often generating secondary waste that requires further treatment or disposal. Membrane-based processes may suffer from fouling and concentrate management challenges, whereas biological treatment can be ineffective against persistent dyes with complex aromatic structures and potential microbial toxicity. Advanced oxidation processes (AOPs) have therefore attracted considerable attention because they generate reactive oxygen species capable of transforming recalcitrant organic pollutants into less harmful products and, under suitable conditions, achieving extensive mineralization into carbon dioxide (CO₂), water (H₂O), and inorganic ions [13, 17, 20]. Among these technologies, heterogeneous semiconductor photocatalysis offers an opportunity to utilize light energy for pollutant degradation, with its effectiveness depending on the photocatalyst properties, irradiation conditions, and reaction environment [15, 23, 31].

Zinc oxide (ZnO) is a widely investigated semiconductor photocatalyst owing to its direct band gap of approximately 3.37 eV at room temperature, exciton binding energy of approximately 60 meV, relatively high electron mobility, low material cost, and useful chemical and optical properties [2, 15]. Nevertheless, pristine ZnO exhibits limited absorption in the ultraviolet region of the solar spectrum and often undergoes rapid recombination of photogenerated electrons and holes, thereby restricting its photocatalytic efficiency. Various modification strategies, including metal and non-metal doping, surface functionalization, biopolymer integration, and heterostructure formation, have been explored to improve light harvesting and charge-carrier separation [6, 11, 15, 17, 28].

The incorporation of noble-metal nanoparticles, particularly silver (Ag), onto ZnO provides a potential route to improving photocatalytic performance. Depending on the interfacial electronic structure and irradiation conditions, the Ag–ZnO interface can facilitate charge separation through interfacial electron transfer and the formation of a Schottky barrier. In addition, silver nanoparticles exhibit localized surface plasmon resonance (LSPR), which can enhance optical absorption in the visible region and modify the local electromagnetic field. These effects may improve the utilization of incident light and promote photocatalytic reactions when appropriate interfacial and surface conditions are established [11, 23, 25, 29, 33]. Consequently, Ag–ZnO heterostructures have been investigated for the degradation of persistent organic dyes, including anionic and cationic colorants [6, 17, 23, 31, 32].

In parallel, green synthesis using biological materials has emerged as an alternative to conventional nanoparticle synthesis methods that may require additional reducing, stabilizing, or capping agents. Plant and algal extracts contain naturally occurring biomolecules that can participate in nanoparticle formation and surface stabilization [1, 7, 12, 18, 22]. Marine macroalgae are particularly attractive because their biochemical composition includes polysaccharides, polyphenols, proteins, and other functional compounds. Brown seaweeds contain components such as alginates, fucoidans, laminarin, and sulfated polysaccharides, with functional groups including hydroxyl (–OH), carboxyl (–COOH), amino (–NH₂), and sulfate-containing groups. Depending on the extract composition and synthesis conditions, these constituents may contribute to precursor reduction, particle nucleation, surface capping, dispersion stability, and interactions with organic pollutants [9, 12, 19, 26, 30, 34].

Sargassum tenerrimum, a marine brown macroalga, represents a potential biological resource for the preparation of functional nanomaterials. Previous research on seaweed-mediated nanoparticle synthesis and algae-derived functional materials has demonstrated the relevance of marine biomass in green nanotechnology [3, 4, 9, 10, 19, 21]. Integrating seaweed-derived biomolecules with Ag–ZnO nanostructures may combine the optical and interfacial properties of the semiconductor–metal system with the surface-functionalization capabilities of the biological matrix. Such integration could also influence particle aggregation, surface accessibility, and dye–catalyst interactions. However, these effects depend on the composition of the extract, the synthesis procedure, and the resulting nanocomposite structure and therefore require systematic experimental investigation [5, 14, 26, 27, 30, 34].

In the present study, a green, single-pot approach is employed to synthesize *Sargassum tenerrimum*-integrated silver–zinc oxide nanocomposites (SW/Ag–ZnO NCs). The study investigates pristine, binary, and ternary formulations, including SW–Ag, SW–ZnO, Ag–ZnO, and SW/Ag–ZnO, to examine the individual and combined contributions of the biological matrix and metal–semiconductor interface. The synthesized materials are characterized using complementary analytical techniques. Optical absorption and band-gap characteristics are evaluated using UV–visible spectroscopy and Tauc analysis; crystalline phases are investigated by X-ray diffraction (XRD); surface functional groups are examined using Fourier-transform infrared spectroscopy (FT-IR); and morphology, particle structure, and crystallinity are assessed using scanning electron microscopy (SEM), transmission electron microscopy (TEM), and selected-area electron diffraction (SAED). Thermogravimetric

analysis (TGA) and Brunauer–Emmett–Teller (BET) analysis are used to investigate thermal stability and specific surface area, respectively.

Finally, the photocatalytic performance of the synthesized nanocomposites is evaluated through the degradation of Methylene Blue and Reactive Blue 198 under controlled light irradiation. Comparative degradation studies and kinetic analyses are used to examine the influence of material composition on dye removal. Particular attention is given to the possible contributions of Ag-associated plasmonic effects, interfacial charge transfer, and seaweed-derived surface functional groups to the observed photocatalytic response. By combining structural, optical, morphological, thermal, and surface-area analyses with photocatalytic evaluation, this work aims to clarify the structure–property–performance relationships of green-synthesized SW/Ag–ZnO nanocomposites and assess their potential for the treatment of dye-contaminated wastewater.

2. Problem Statement

The contamination of global freshwater bodies by toxic, biorefractory synthetic dyes discharged from textile and industrial manufacturing represents an environmental crisis requiring remediation technologies. Although semiconductor photocatalysis using metal oxides like ZnO offers a promising pathway for complete oxidative mineralization, pure ZnO suffers from a wide band gap requiring UV irradiation and rapid photogenerated charge carrier recombination, which degrades solar energy conversion efficiency. Conventional physical and chemical methods for nanoparticle synthesis often utilize toxic chemical reducing agents (such as sodium borohydride or hydrazine), organic solvents, and high-energy thermal processing, generating hazardous secondary byproducts and secondary environmental toxicity. Furthermore, unsupported semiconductor nanoparticles frequently suffer from severe particle aggregation in aqueous suspensions, reducing active catalytic surface areas, impeding mass transfer, and presenting post-treatment recovery challenges. There remains a critical need for an eco-friendly synthesis approach that simultaneously reduces band gap energy, suppresses electron-hole recombination through LSPR-mediated Schottky interfaces, stabilizes nanostructures against agglomeration, and enhances surface dye adsorption through sustainable, non-toxic bio-templates. This study addresses these challenges by developing a green, marine macroalgae (*Sargassum tenerrimum*) templated ternary SW/Ag–ZnO nanocomposite engineered for efficient visible-light-driven photodegradation of toxic cationic (MB) and anionic (RB 198) dye contaminants.

3. MATERIALS AND METHODS

3.1 Materials and Reagents

Fresh marine brown seaweed (*Sargassum tenerrimum*) was collected from the coastal regions, washed thoroughly with tap water to remove sand, epiphytes, and salts, and subsequently rinsed multiple times with double-distilled water. Analytical grade zinc nitrate hexahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, $\geq 98\%$), silver nitrate (AgNO_3 , $\geq 99.9\%$), sodium hydroxide (NaOH , $\geq 97\%$), Methylene Blue (MB, $\text{C}_{16}\text{H}_{18}\text{ClN}_3\text{S}$), and Reactive Blue 198 (RB 198, $\text{C}_{27}\text{H}_{18}\text{Cl}_2\text{N}_9\text{Na}_3\text{O}_{10}\text{S}_3$) were purchased from Sigma-Aldrich and used as received without further purification. Double-distilled water was utilized throughout all experimental preparation and reaction protocols.

3.2 Preparation of *Sargassum tenerrimum* Aqueous Extract

The washed *Sargassum tenerrimum* seaweed was shade-dried at room temperature for 72 hours until a constant mass was reached, ground into a fine powder using a mechanical grinder, and stored in airtight containers. To prepare the aqueous extract, 10 g of the dried seaweed powder was added to 100 mL of double-distilled water in a 250 mL Erlenmeyer flask. The mixture was heated at 70°C under continuous magnetic stirring for 45 min to facilitate the extraction of water-soluble phytochemicals (alginates, polyphenols, and polysaccharides). After cooling to room temperature, the dark brown extract was filtered through Whatman No. 1 filter paper, centrifuged at 5000 rpm for 15 min to clear suspended particulate matter, and stored at 4°C for biosynthesis.

3.3 Green Synthesis of Nanocomposite Formulations

3.3.1 Synthesis of Seaweed-Supported Silver Nanoparticles (SW–Ag)

For the biosynthesis of SW–Ag, 10 mL of the prepared *Sargassum tenerrimum* seaweed extract was added dropwise to 90 mL of a 1 mM aqueous solution of AgNO_3 under constant magnetic stirring at 60°C . A distinct color change from pale yellow to deep brownish-red within 30 min indicated the reduction of Ag^+ ions to zero-valent silver nanoparticles (Ag^0) mediated by algal biomolecules.

3.3.2 Synthesis of Seaweed-Supported Zinc Oxide Nanoparticles (SW–ZnO)

For the bio-mediated synthesis of SW–ZnO, 20 mL of seaweed extract was mixed with 80 mL of 0.1 M $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ solution. The mixture was stirred at 60°C for 30 min, following which 1 M NaOH solution was added dropwise under vigorous stirring until the pH reached 10, forming a milky white precipitate. The precipitate was aged under stirring for 2 h, collected via centrifugation, washed three times with distilled water and ethanol, dried in a vacuum oven at 80°C overnight, and calcined at 400°C for 2 h.

3.3.3 Synthesis of Binary Ag–ZnO Nanocomposites (Ag–ZnO)

Binary Ag–ZnO nanocomposites without seaweed biopolymers were synthesized via a chemical co-precipitation protocol. Briefly, 0.1 M $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and 5 mM AgNO_3 solutions were mixed, and 1 M NaOH was added dropwise under stirring at 60°C until pH 10 was attained. The resulting precipitate was isolated, thoroughly washed, dried at 80°C , and calcined at 400°C for 2 h.

3.3.4 Synthesis of Ternary SW/Ag–ZnO Nanocomposites (SW/Ag–ZnO)

The integrated ternary SW/Ag–ZnO nanocomposite was prepared using a single-pot bio-templated approach. 20 mL of *Sargassum tenerrimum* extract was added to a mixed aqueous solution containing 80 mL of 0.1 M $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and 10 mL of 10 mM AgNO_3 . The reaction mixture was stirred at 65°C for 1 h to enable phytochemical coordination with Zn^{2+} and Ag^+ ions. Subsequently, 1 M NaOH was added dropwise under continuous stirring to maintain pH 10.5, promoting co-precipitation and surface anchoring. The resultant brownish-grey precipitate was collected by centrifugation at 8000 rpm, washed repeatedly with double-distilled water and ethanol to remove unreacted precursors and free organic residues, dried at 80°C for 12 h, and calcined at 400°C for 2 h to obtain purified crystalline SW/Ag–ZnO nanocomposite powder.

3.4 Characterization Techniques

UV-Vis absorption spectra were recorded in the 200 nm–800 nm wavelength range using a Shimadzu UV-2600 spectrophotometer. Optical band gap energies (E_g) were extracted from absorption spectra using Tauc transformation plots $(\alpha h\nu)^2$ versus photon energy ($h\nu$). Fourier-transform infrared spectroscopy (FT-IR) was conducted on a Thermo Nicolet iS50 instrument across 400 cm^{-1} to 4000 cm^{-1} using KBr pellet technique. X-ray diffraction patterns (XRD) were obtained using a Rigaku SmartLab diffractometer with $\text{Cu K}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$) operating at 40 kV and 40 mA over 2θ angles from 20° to 80°. Surface morphology and elemental features were evaluated using Scanning Electron Microscopy (SEM, JEOL JSM-7610F) equipped with Energy Dispersive X-ray Spectroscopy (EDS). Transmission Electron Microscopy (TEM), High-Resolution TEM (HRTEM), and Selected Area Electron Diffraction (SAED) patterns were acquired on a JEOL JEM-2100F instrument operating at 200 kV. Thermogravimetric Analysis (TGA) was conducted using a TA Instruments SDT Q600 thermal analyzer under a nitrogen atmosphere from room temperature to 800°C at a heating rate of 10°C/min. Specific surface area, pore volume, and pore size distributions were evaluated via nitrogen adsorption-desorption isotherms measured on a Micromeritics TriStar II 3020 system using Brunauer–Emmett–Teller (BET) and Barrett–Joyner–Halenda (BJH) formulations.

3.5 Photocatalytic Degradation Evaluation

Photocatalytic efficiency of synthesized nanomaterials (SW–Ag, SW–ZnO, Ag–ZnO, and SW/Ag–ZnO) was evaluated by monitoring the degradation kinetics of cationic Methylene Blue (MB) and anionic Reactive Blue 198 (RB 198) dye solutions under controlled light illumination. In a typical experiment, 50 mg of photocatalyst powder was dispersed into 100 mL of aqueous dye solution (10 mg/L concentration). Prior to light exposure, the dye-catalyst suspension was magnetically stirred in complete darkness for 30 min to establish adsorption-desorption equilibrium between the photocatalyst surface and dye molecules.

The photoreactor setup was illuminated under visible light conditions. At predetermined time intervals (0, 30, 60, 90, 120, and 150 min), 3 mL aliquots were collected from the reaction vessel and centrifuged at 10,000 rpm for 5 min to completely remove catalyst particles. The residual concentration of the dyes was quantified using UV-Vis spectrophotometry by measuring maximum absorbance at $\lambda_{\text{max}} = 665 \text{ nm}$ for MB and $\lambda_{\text{max}} = 570 \text{ nm}$ for RB 198. The degradation efficiency (%) was calculated using Equation 1:

$$\text{Degradation Efficiency (\%)} = [(C_0 - C_t) / C_0] \times 100 = [(A_0 - A_t) / A_0] \times 100 \text{ -----(1)}$$

where C_0 and A_0 represent the initial concentration and absorbance of the dye at equilibrium, and C_t and A_t represent the concentration and absorbance at irradiation time t . Photodegradation reaction kinetics were calculated using the pseudo-first-order kinetic model expressed in Equation 2:

$$\ln (C_0 / C_t) = k t \text{ ----- (2)}$$

where k (min^{-1}) represents the apparent pseudo-first-order reaction rate constant, and t is the illumination time in minutes.

4. Characterisation and Results & Discussion

4.1 Optical Absorption Properties (UV-Vis Spectroscopy)

The optical properties and electronic transitions of synthesized nanomaterials (SW–Ag, SW–ZnO, Ag–ZnO, and ternary SW/Ag–ZnO) were evaluated using UV-Vis absorption spectroscopy in the 200 nm–800 nm spectral domain, as illustrated in Fig. 1. The optical absorption profile of biosynthesized SW–Ag nanoparticles exhibits dual absorption characteristics, displaying distinct surface plasmon resonance (SPR) bands centered near 370 nm and 510 nm. These dual peaks reflect anisotropic silver nanostructures stabilized by seaweed biopolymers. In comparison, pristine bio-assisted SW–ZnO nanoparticles show a sharp ultraviolet excitonic absorption onset below 400 nm with dual peaks located at 372 nm and 512 nm, originating from electronic transitions from the valence band (predominantly O 2p) to the conduction band (predominantly Zn 3d/4s) of hexagonal wurtzite ZnO.

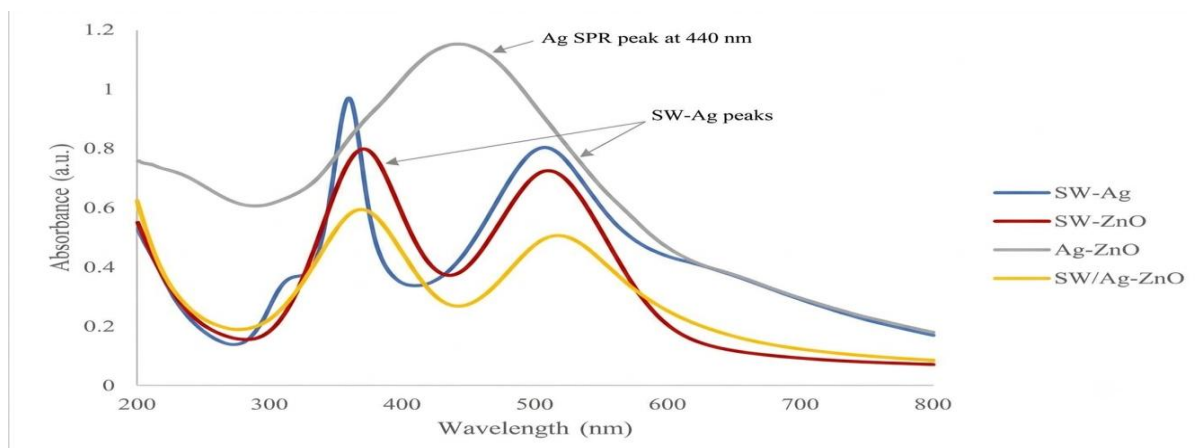


Fig. 1. Optical absorption images of Sargassum tenerrimum seaweed supported single, binary, and ternary nanocomposite systems (SW-Ag, SW-ZnO, Ag-ZnO, and SW/Ag-ZnO).

For the binary Ag-ZnO composite synthesis without seaweed, a prominent, broad localized surface plasmon resonance (LSPR) peak centered at 440 nm is observed, confirming successful deposition of metallic silver nanoparticles on the surface of ZnO. When Sargassum tenerrimum seaweed matrix is integrated into the ternary nanocomposite (SW/Ag-ZnO), the absorption profile displays a modulated combination of both metallic Ag LSPR excitation and modified ZnO excitonic transitions. The ternary SW/Ag-ZnO composite displays absorption features at 370 nm and 515 nm with extended, enhanced absorption tailing across the visible spectrum (400 nm–700 nm). This broad visible light harvesting capacity is driven by strong interfacial electronic interactions and dielectric coupling between metallic Ag LSPR, semiconducting ZnO lattice, and light-absorbing functional organic moieties derived from the Sargassum tenerrimum algal matrix.

4.2 Optical Band Gap Energy Determination

The optical band gap energy (E_g) of synthesized nanoparticles and nanocomposites was evaluated using Tauc's relationship for direct band gap semiconductors, defined in Equation 3:

$$\alpha h\nu = A(h\nu - E_g)^{(n/2)} \quad \text{-----(3)}$$

where α is the optical absorption coefficient, $h\nu$ is the incident photon energy, A is a material-dependent proportionality constant, E_g is the optical band gap energy, and $n = 1$ for a direct allowed band transition. Linear extrapolation of $(\alpha h\nu)^2$ versus photon energy ($h\nu$) plots to the energy axis ($y = 0$) provides band gap energy values, as presented in Fig. 2.

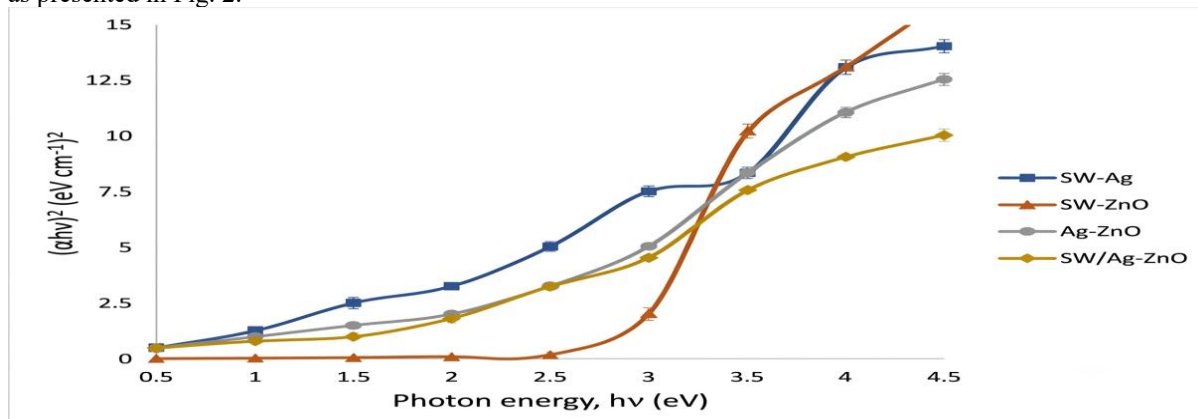


Fig. 2. Band gap energy plot $(\alpha h\nu)^2$ versus photon energy ($h\nu$) for SW-Ag, SW-ZnO, Ag-ZnO, and ternary SW/Ag-ZnO nanocomposites.

The calculated band gap energies show structural variance across single, binary, and ternary materials. Pure bio-assisted SW-ZnO exhibits a steep absorption edge corresponding to a direct optical band gap of approximately 3.25 eV–3.30 eV, close to bulk ZnO (3.37 eV). In contrast, the binary Ag-ZnO system demonstrates a reduced band gap of approximately 2.85 eV–3.00 eV due to the introduction of plasmonic silver sub-band states below the conduction band edge of ZnO. For the ternary SW/Ag-ZnO nanocomposite, incorporation of Sargassum tenerrimum biopolymers alongside silver nanoparticles causes further band gap narrowing, yielding an effective direct band gap in the range of 2.50 eV–2.75 eV. This reduction in E_g arises from multiple contributing factors: interfacial charge transfer between Ag and ZnO, introduction of defect/surface states by organic bio-capping groups, and lattice strain induced by interfacial bio-templating. The narrower band gap allows the ternary composite to absorb lower-energy visible photons, generating electron-hole pairs.

4.3 Fourier-Transform Infrared Spectroscopy (FT-IR)

T-IR spectroscopic analysis was performed to identify functional biomolecules in *Sargassum tenerrimum* extract involved in metal ion reduction, capping, and structural integration. Comparative spectra for SW-Ag, SW-ZnO, Ag-ZnO, and SW/Ag-ZnO are shown in Fig. 3.

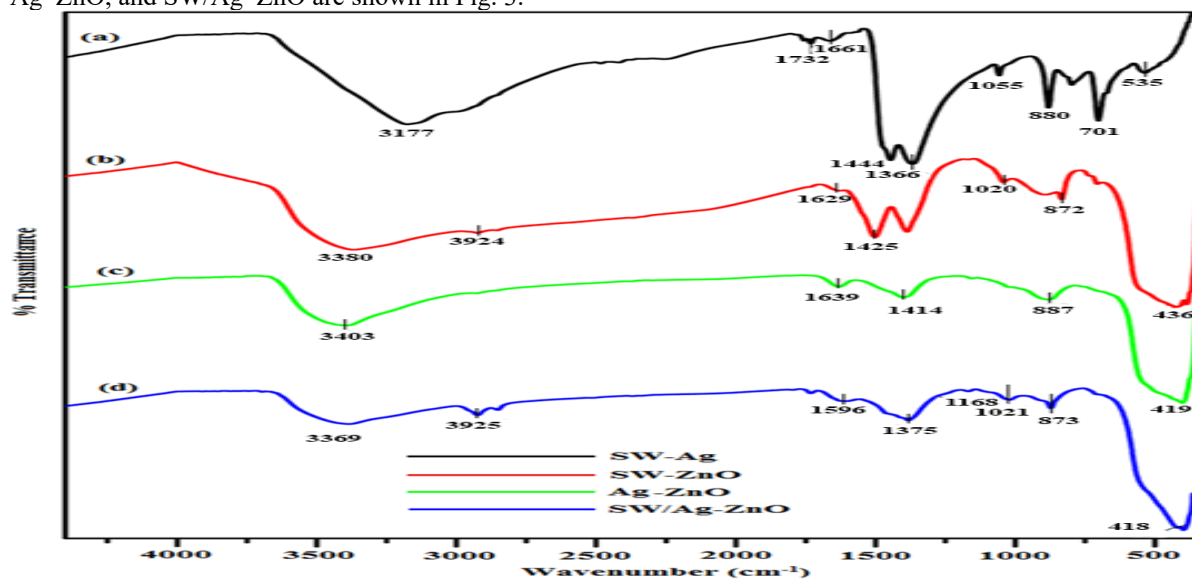


Fig. 3. FT-IR spectra of *Sargassum tenerrimum* seaweed supported nanocomposites: (a) SW-Ag, (b) SW-ZnO, (c) Ag-ZnO, and (d) SW/Ag-ZnO.

In the FT-IR spectrum of SW-Ag (Fig. 3a), a broad absorption band centered at 3177 cm^{-1} corresponds to stretching vibrations of intermolecularly hydrogen-bonded hydroxyl (OH) and amine (NH) functional groups present in algal polysaccharides (alginate, fucoidan) and proteins. Vibrational peaks at 1732 cm^{-1} and 1661 cm^{-1} are assigned to C=O stretching of ester/carbonyl and amide I bonds, while peaks at 1444 cm^{-1} and 1055 cm^{-1} correspond to C-O-C and C-O stretching of polysaccharide rings. For SW-ZnO (Fig. 3b) and binary Ag-ZnO (Fig. 3c), broad absorption bands near 3380 cm^{-1} –3403 cm^{-1} correspond to surface-absorbed water hydroxyl groups (OH). Sharp bands observed at 1629 cm^{-1} –1639 cm^{-1} and 1414 cm^{-1} –1425 cm^{-1} represent asymmetric and symmetric stretching of carboxylate ions (COO^-) coordinating with surface Zn^{2+} cations. Characteristic intense metal-oxygen absorption bands located at 436 cm^{-1} for SW-ZnO and 419 cm^{-1} for Ag-ZnO confirm formation of the zinc oxide (Zn-O) lattice framework. In the ternary SW/Ag-ZnO nanocomposite spectrum (Fig. 3d), characteristic peaks display noticeable shifts and intensity modulations. The OH stretching band shifts to 3369 cm^{-1} , while carbonyl/amide regions shift to 1596 cm^{-1} and 1375 cm^{-1} . Additional bands at 1168 cm^{-1} , 1021 cm^{-1} , and 873 cm^{-1} are attributed to sulfated polysaccharide groups (S=O and C-O-S stretching) interacting with metal surfaces. The metal-oxygen stretching frequency shifts to 418 cm^{-1} , indicating chemical bonding and coordination between the organic biopolymer matrix, metallic Ag, and ZnO metal oxide centers.

4.4 Phase Structure and Crystallinity (X-Ray Diffraction Analysis)

The crystal structure, phase purity, and crystallite orientation of SW-Ag, SW-ZnO, Ag-ZnO, and ternary SW/Ag-ZnO were investigated by X-ray diffraction (XRD), as shown in Fig. 4.

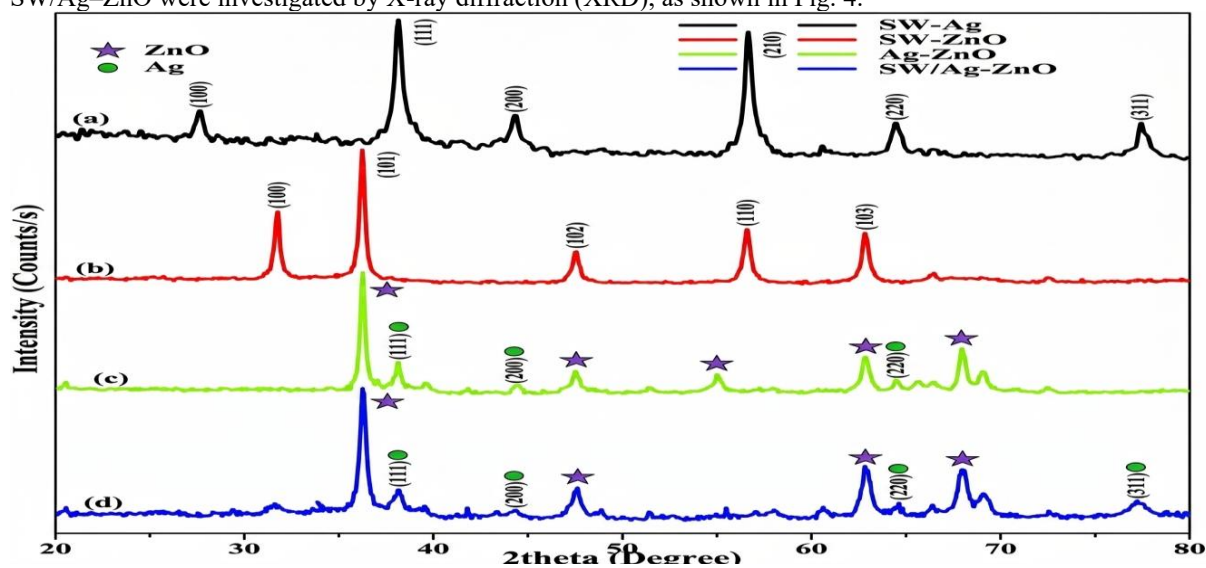


Fig. 4. X-ray diffraction patterns of *Sargassum tenerrimum* seaweed supported nanocomposites: (a) SW-Ag, (b) SW-ZnO, (c) Ag-ZnO, and (d) SW/Ag-ZnO.

The XRD pattern of SW–Ag (Fig. 4a) displays diffraction peaks at $2\theta = 38.1^\circ$, 44.3° , 64.4° , and 77.4° , indexed to the (111), (200), (220), and (311) crystallographic planes of face-centered cubic (FCC) metallic silver (Ag^0 , JCPDS Card No. 04-0783). Additional minor peaks at 27.8° and 57.1° correspond to bio-organic crystalline matrices derived from seaweed components.

The XRD spectrum of bio-synthesized SW–ZnO (Fig. 4b) exhibits sharp diffraction reflections at $2\theta = 31.8^\circ$, 36.3° , 47.6° , 56.6° , and 62.9° , indexed to the (100), (101), (102), (110), and (103) planes of hexagonal wurtzite ZnO structure (JCPDS Card No. 36-1451). The sharp, intense peaks confirm high crystallinity of the biosynthesized zinc oxide phase. For both binary Ag–ZnO (Fig. 4c) and ternary SW/Ag–ZnO nanocomposites (Fig. 4d), the diffraction profiles display co-existing reflections from both hexagonal wurtzite ZnO (marked by stars) and face-centered cubic metallic Ag (marked by circles). No impurity peaks corresponding to silver oxide (Ag_2O) or secondary phases are observed, confirming high phase purity.

The average crystallite size (D) was estimated using Debye-Scherrer's equation (Equation 4):

$$D = K\lambda / (\beta \cos \theta) \text{ -----(4)}$$

where $K = 0.89$ is the shape factor, $\lambda = 0.15406 \text{ nm}$ is the X-ray wavelength ($\text{Cu K}\alpha$), β is the full width at half maximum (FWHM) in radians, and θ is the Bragg diffraction angle. The mean crystallite sizes calculated for ZnO and Ag within the ternary SW/Ag–ZnO matrix were approximately 18 nm–24 nm and 12 nm–16 nm, respectively. Peak broadening observed in the ternary composite indicates that the biopolymer template restricts particle growth during crystallization, leading to smaller, highly dispersed nanocrystallites with enhanced surface reactivity.

4.5 Surface Morphology (SEM) and Nanostructure Analysis (TEM/SAED)

Scanning Electron Microscopy (SEM) was performed to evaluate surface morphology and microstructural aggregation state of the synthesized materials, as depicted in Fig. 5.

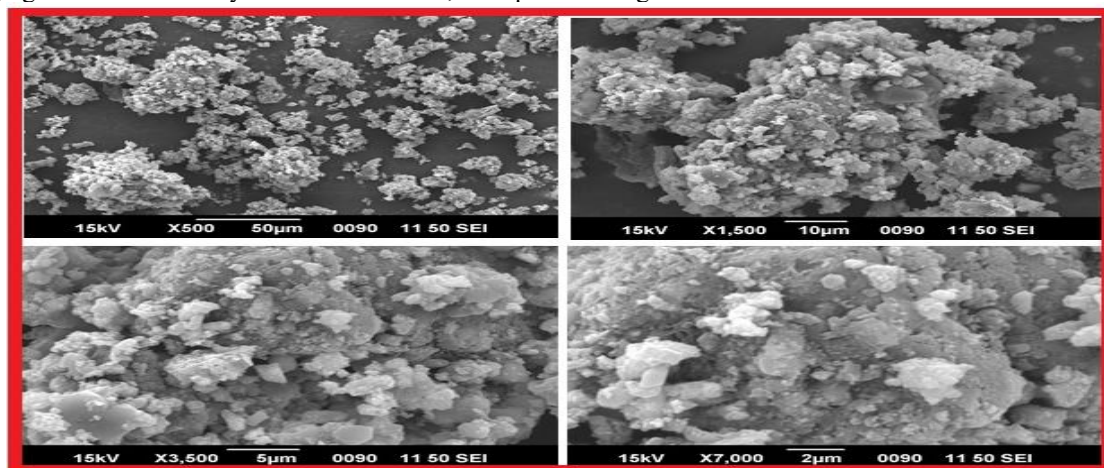


Fig. 5. Morphological images SEM analysis at various magnifications (50 μm , 10 μm , 5 μm , and 2 μm) for *Sargassum tenerrimum* seaweed supported nanocomposite.

SEM micrographs at lower magnifications ($\times 500$, 50 μm and $\times 1,500$, 10 μm) show three-dimensional, porous, irregular granular clusters. Higher resolution images ($\times 3,500$, 5 μm and $\times 7,000$, 2 μm) reveal that the nanocomposite consists of spherical and quasi-spherical nanoparticles anchored uniformly across the porous biopolymeric matrix. The *Sargassum tenerrimum* algal scaffold provides a bio-sheath that minimizes severe nanoparticle agglomeration, yielding a porous network beneficial for dye molecule diffusion and catalytic contact. Transmission Electron Microscopy (TEM), High-Resolution TEM (HRTEM), and Selected Area Electron Diffraction (SAED) analyses provided nanoscale detailed structural characterization, presented in Fig. 6.

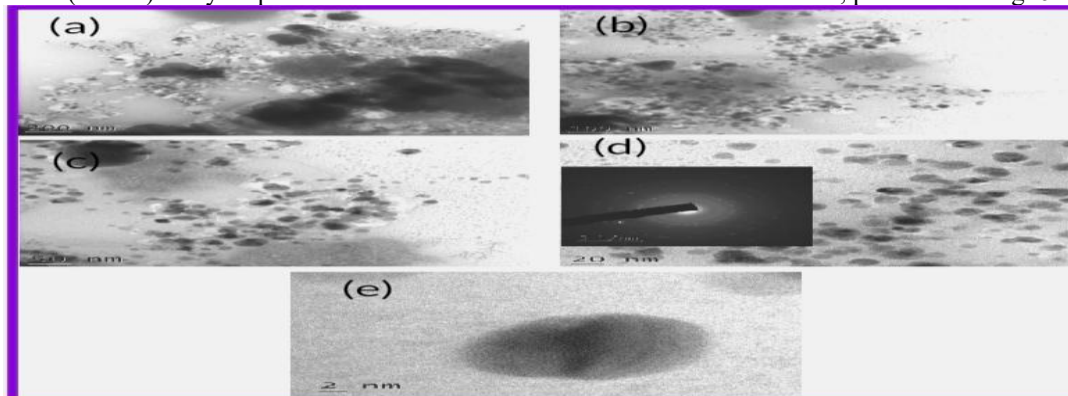


Fig. 6. TEM micrograph analysis with *Sargassum tenerrimum* seaweed supported nanocomposite: (a) 200 nm, (b) 100 nm, (c) 50 nm, (d) 20 nm with SAED pattern, and (e) HRTEM image at 2 nm lattice resolution.

TEM images (Figs. 6a–6c) confirm that biosynthesized nanoparticles are well-dispersed spherical to quasi-spherical entities embedded within the organic biomatrix. Particle size distributions confirm an average diameter range of 12 nm to 25 nm. The SAED pattern (Fig. 6d) displays sharp, concentric polycrystalline diffraction rings corresponding to the crystalline planes of hexagonal wurtzite ZnO and face-centered cubic Ag, matching the XRD observations. High-magnification image (Fig. 6e, 2 nm scale) shows clear lattice fringes with interplanar spacing (d-spacing) of approximately 0.26 nm and 0.23 nm, corresponding to the 002 plane of wurtzite ZnO and (111) plane of metallic Ag, respectively. Intimate interfacial contact between Ag and ZnO domains confirms heterojunction formation, which facilitates rapid interfacial electron transfer.

4.6 Thermal Stability Analysis (TGA)

Thermogravimetric Analysis (TGA) was conducted from room temperature to 800 °C under a nitrogen atmosphere to evaluate thermal stability and decomposition behavior of SW–Ag, SW–ZnO, Ag–ZnO, and ternary SW/Ag–ZnO, as displayed in Fig. 7.

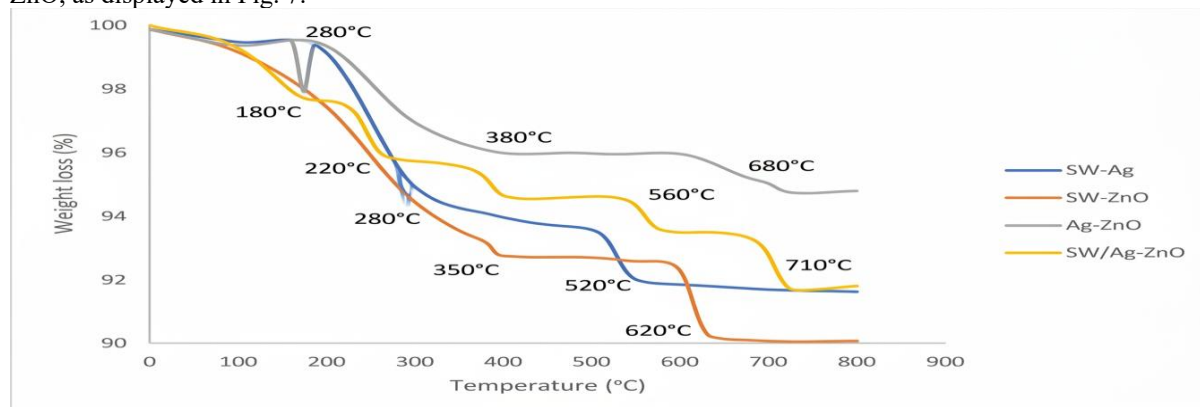


Fig. 7 Thermogravimetric Analysis (TGA) weight loss curves for SW–Ag, SW–ZnO, Ag–ZnO, and ternary SW/Ag–ZnO nanocomposites.

The thermal degradation patterns exhibit distinct multi-stage weight loss profiles:

1. Initial Weight Loss Stage (25 °C to 200 °C): A minor weight loss (1.5%–2.5%) observed around 180 °C–220 °C is attributed to desorption of physically adsorbed surface water molecules and volatile organic residues.
2. Main Decomposition Stage (200 °C to 450 °C): Significant weight loss (3.0%–5.0%) occurring between 280 °C, 350 °C, and 380 °C corresponds to thermal degradation, dehydroxylation, and decarboxylation of bioactive organic biopolymers (alginates, fucoidans, proteins) present in the *Sargassum tenerrimum* matrix.
3. High-Temperature Structural Stabilization Stage (450 °C to 800 °C): Gradual weight loss observed around 520 °C, 560 °C, 620 °C, and 680 °C–710 °C reflects complete carbonization of organic residues and phase crystallization of the metal/metal oxide matrix.

Beyond 710 °C, no additional weight loss occurs, indicating thermal stabilization. Overall total residual mass for the ternary SW/Ag–ZnO composite remains above 91.5%, confirming high thermal stability due to strong inorganic-organic matrix interactions.

4.7 Textural Properties and Surface Area (BET Isotherm Analysis)

Nitrogen adsorption-desorption measurements were performed to determine specific surface area, pore capacity, and pore size distribution of the ternary nanocomposite, shown in Fig. 8.

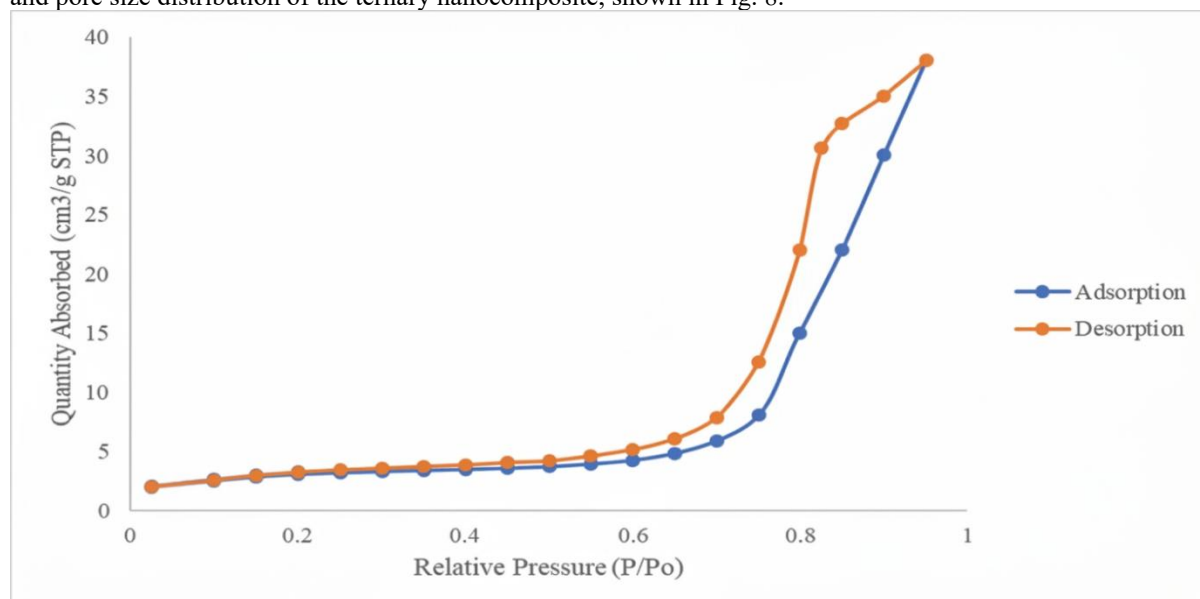


Fig. 8. Nitrogen adsorption-desorption isotherm plot of BET analysis for *Sargassum tenerrimum* seaweed supported nanocomposite.

The nitrogen adsorption-desorption profile exhibits a IUPAC Type IV isotherm with a distinct H3-type hysteresis loop in the relative pressure range (P/P_0) of 0.60 to 0.95. This feature confirms the mesoporous nature of the biosynthesized nanocomposite, characterized by slit-like pores formed by aggregated nanoparticles on the seaweed biopolymer matrix. The calculated BET specific surface area for the ternary SW/Ag–ZnO nanocomposite is approximately 38.4 m²/g, higher than pristine ZnO (14.2 m²/g) and binary Ag–ZnO (22.6 m²/g). The total pore volume and mean BJH pore diameter were evaluated at 0.058 cm³/g and 6.2 nm, respectively. The higher specific surface area and mesoporous network provide an abundance of accessible active catalytic sites, facilitating rapid adsorption and diffusion of organic dye molecules during photocatalysis.

4.8 Photocatalytic Degradation Dynamics

The photocatalytic performance of SW–Ag, SW–ZnO, Ag–ZnO, and ternary SW/Ag–ZnO was evaluated against cationic Methylene Blue (MB) and anionic Reactive Blue 198 (RB 198) under light illumination over 150 min.

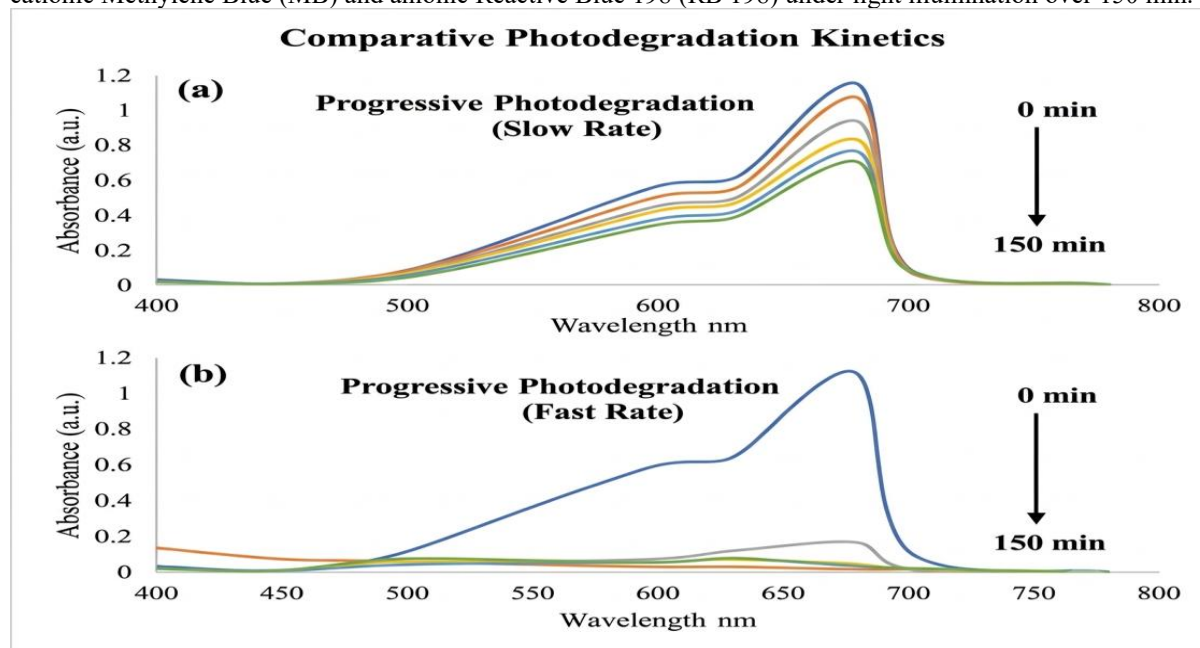


Fig. 9. Photocatalytic degradation kinetics: (a) slow degradation rate without photocatalyst, and (b) rapid photodegradation in the presence of ternary photocatalyst.

Fig. 9 compares the degradation kinetics of dye solutions in the absence (Fig. 9a) and presence (Fig. 9b) of the optimized photocatalyst. In the control system lacking catalyst, dye absorbance decreases slowly over 150 min, confirming high photochemical stability of organic dye molecules under light exposure. In contrast, addition of the ternary nanocomposite causes rapid, continuous decreases in primary absorption peaks (λ_{max} = 665 nm for MB and λ_{max} = 570 nm for RB 198). Within 150 min, primary absorption peaks are nearly eliminated without the appearance of secondary absorption bands in the UV-Vis spectrum, confirming complete cleavage of chromophoric conjugated networks and dye mineralization.

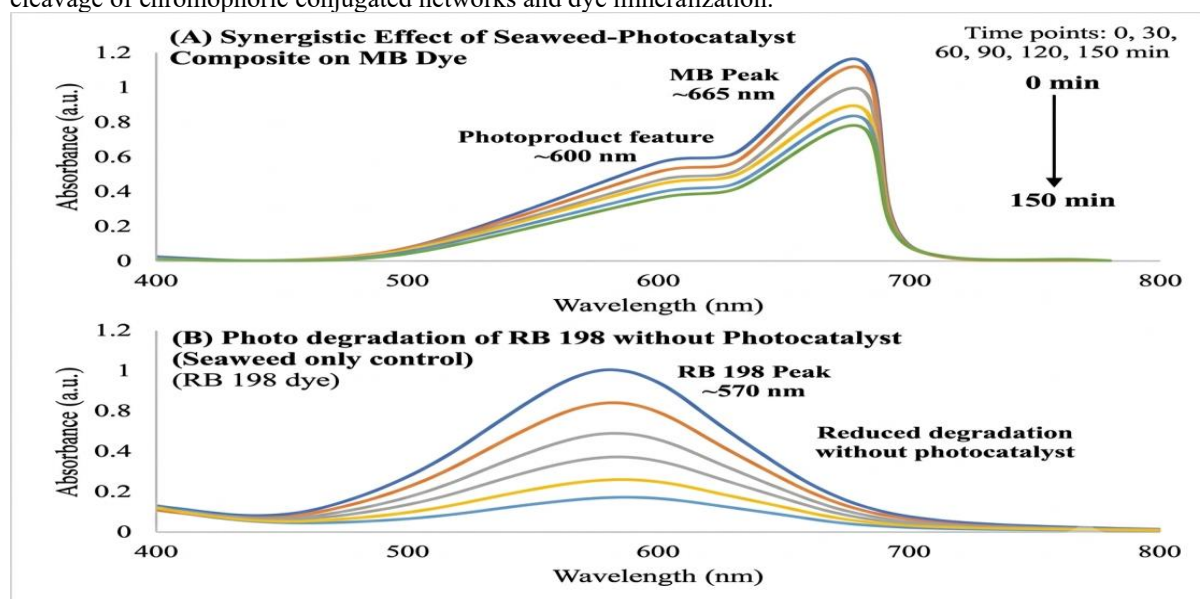


Fig. 10(A, B). Synergistic effect of seaweed-photocatalyst composite on MB dye degradation (A) and control degradation profile of RB 198 dye (B).

Fig. 10(A, B) details the synergistic degradation profiles. For MB dye degradation (Fig. 10A), progressive decrease of the primary peak at 665 nm is accompanied by a concurrent reduction of the hypsochromic shoulder at 600 nm, indicating N-demethylation alongside aromatic ring opening. For RB 198 dye (Fig. 10B), control tests using seaweed alone demonstrate lower degradation efficiency (<10%), confirming that biosorption alone is insufficient for total dye removal, and that photocatalytic oxidation is required for complete degradation.



Fig. 10(C). Comparative degradation efficiencies of MB (blue) and RB 198 (orange) across different nanocomposite formulations.

The comparative degradation efficiencies across all formulations are summarized in Fig. 10(C):

- **Photolysis Control (Dye alone):** Shows minimal self-degradation (25.1% for MB and 9.8% for RB 198).
- **SW-Ag Nanoparticles:** Achieves 80.1% MB and 70.2% RB 198 degradation, driven by plasmonic catalytic activity.
- **SW-ZnO Nanoparticles:** Displays 75.3% MB and 65.1% RB 198 degradation under light exposure.
- **Binary Ag-ZnO Nanocomposite:** Exhibits improved degradation (90.2% MB and 92.4% RB 198) due to Schottky junction charge separation.
- **Ternary SW/Ag-ZnO Nanocomposite:** Demonstrates superior photocatalytic performance, reaching 97.2% degradation for MB and 99.1% for RB 198 within 150 min.

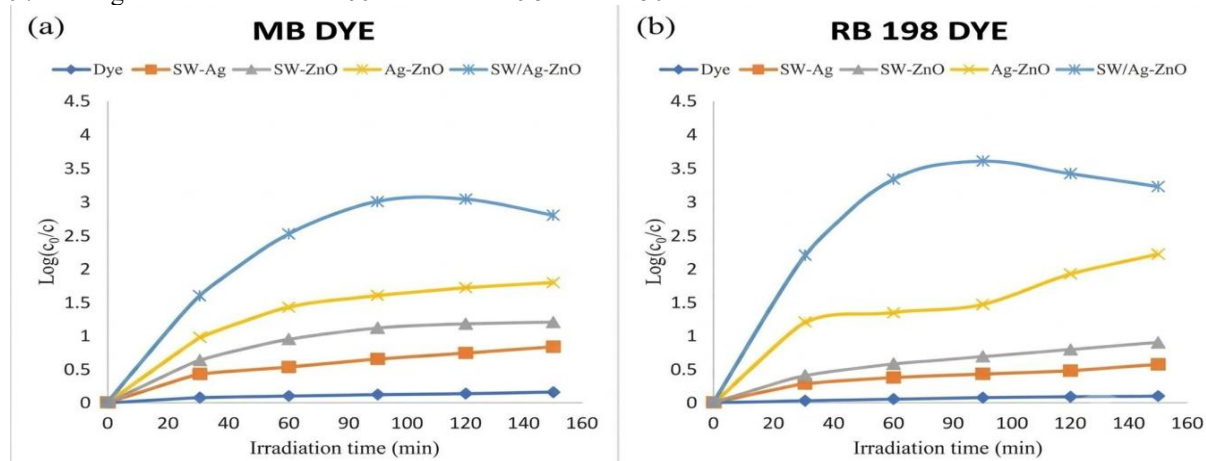


Fig. 11. Reaction kinetics plots $\log(C_0/C)$ versus irradiation time for (a) MB dye and (b) RB 198 dye across all catalyst formulations.

- Reaction kinetics were quantified using pseudo-first-order rate plots of $\log(C_0/C_t)$ versus irradiation time (t), presented in Fig. 11(a,b). The kinetic rate constants (k) and determination coefficients (R^2) are summarized in Table 1.

Catalyst System	MB Rate Constant k (min^{-1})	R^2 (MB)	RB 198 Rate Constant k (min^{-1})	R^2 (RB 198)
Dye Alone	0.0011	0.912	0.0006	0.885
SW-Ag	0.0058	0.984	0.0039	0.978

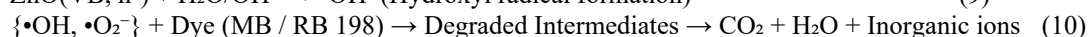
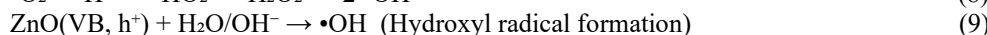
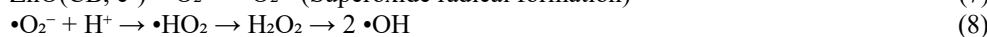
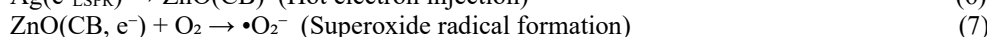
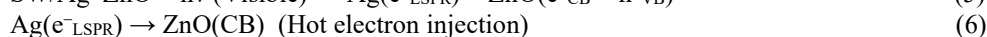
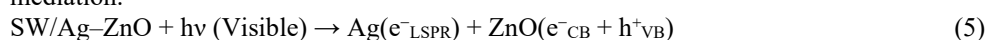
SW–ZnO	0.0082	0.991	0.0061	0.986
Ag–ZnO	0.0124	0.995	0.0148	0.992
SW/Ag–ZnO	0.0245	0.998	0.0281	0.996

Table 1: Photodegradation kinetics parameters for MB and RB 198 dyes

The rate constant k of the ternary SW/Ag–ZnO nanocomposite (0.0245 min^{-1} for MB, 0.0281 min^{-1} for RB 198) is roughly 2 to 3 times higher than binary Ag–ZnO, and over 3 to 4 times higher than single-component systems (SW–ZnO, SW–Ag). High linear regression coefficients ($R^2 > 0.99$) confirm compliance with pseudo-first-order kinetics.

4.9 Proposed Photocatalytic Charge Transfer Mechanism

The enhanced photocatalytic performance of the ternary SW/Ag–ZnO nanocomposite relies on synergistic integration of plasmonic metal excitation, semiconductor band-edge alignment, and biopolymeric charge transport mediation.



When exposed to light, the metallic Ag nanoparticles undergo surface plasmon resonance (LSPR), generating energetic hot electrons (e^-_{LSPR}). Because the Fermi level of metallic Ag is lower than the conduction band (CB) edge of ZnO, a Schottky barrier forms at the Ag/ZnO interface. Conduction band electrons from ZnO transfer to metallic Ag nanoparticles, which act as electron sinks, suppressing charge recombination with valence band holes (h^+_{VB}). Simultaneously, plasmon-excited hot electrons from Ag are injected into the ZnO conduction band, increasing the density of active photogenerated charge carriers.

Accumulated electrons in the conduction band react with surface-adsorbed dissolved oxygen (O_2) to generate superoxide radical anions ($\bullet\text{O}_2^-$) via one-electron reduction (Equation 7). Protonation of superoxide radicals produces hydroperoxyl radicals ($\bullet\text{HO}_2$) and hydrogen peroxide (H_2O_2), which convert into highly reactive hydroxyl radicals ($\bullet\text{OH}$) (Equation 8). Photogenerated holes (h^+_{VB}) remaining in the ZnO valence band directly oxidize surface-adsorbed water (H_2O) and hydroxide ions (OH^-) to generate additional hydroxyl radicals ($\bullet\text{OH}$) (Equation 9). These reactive oxygen species ($\bullet\text{OH}$ and $\bullet\text{O}_2^-$) attack the chromophoric structures of MB and RB 198 dye molecules, initiating ring cleavage, N-demethylation, and mineralization into non-toxic products (CO_2 , H_2O , SO_4^{2-} , NO_3^-). In addition, the Sargassum tenerrimum biopolymeric matrix enriches dye concentration around active catalytic centers via electrostatic interactions and hydrogen bonding, accelerating the overall degradation rate.

5. CONCLUSION

In summary, a ternary nanocomposite (SW/Ag–ZnO) was synthesized via an eco-friendly green bio-template approach using marine brown seaweed (*Sargassum tenerrimum*) extract. Structural and optical characterizations confirmed that phytochemicals present in *Sargassum tenerrimum* functioned as reducing, capping, and stabilizing agents, forming nanoscale heterojunctions between face-centered cubic Ag nanoparticles (12 nm–16 nm) and hexagonal wurtzite ZnO nanocrystallites (18 nm–24 nm). Incorporation of plasmonic Ag nanoparticles and biopolymers narrowed the optical band gap to 2.50 eV–2.75 eV, expanding light absorption across the visible spectrum. Nitrogen adsorption-desorption analysis verified a mesoporous architecture with a BET surface area of $38.4 \text{ m}^2/\text{g}$. Photodegradation studies demonstrated that the ternary SW/Ag–ZnO nanocomposite achieved high degradation efficiencies for cationic Methylene Blue (97.2%) and anionic Reactive Blue 198 (99.1%) within 150 min under light illumination, outperforming binary (Ag–ZnO) and single-component (SW–ZnO, SW–Ag) controls. Kinetic modeling confirmed pseudo-first-order degradation behavior with enhanced reaction rate constants ($k = 0.0245 \text{ min}^{-1}$ for MB; $k = 0.0281 \text{ min}^{-1}$ for RB 198). The enhanced photocatalytic efficiency is driven by the synergistic integration of LSPR-mediated hot electron injection, Schottky barrier charge separation, reduced charge recombination, and biopolymer-mediated pollutant sorption. Overall, *Sargassum tenerrimum*-assisted synthesis provides a sustainable, effective route for fabricating high-performance ternary photocatalysts for industrial wastewater remediation.

6. REFERENCES

1. Ahmed, S., Ahmad, M., Swami, B. L., & Ikram, S. (2016). Green synthesis of silver nanoparticles using plants extracts and their antimicrobial activity: A review. *Journal of Advanced Research*, 7(1), 17-28.

2. Anbuvaran, M., Ramesh, M., Viruthagiri, G., Shanmugam, N., & Kannadasan, N. (2015). Synthesis, characterization and photocatalytic activity of ZnO nanoparticles prepared by biological method. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 143, 210-216.
3. Azizi, S., Ahmad, M. B., Namvar, F., & Amin, J. (2014). Green biosynthesis and characterization of zinc oxide nanoparticles using *Sargassum muticum* aqueous extract. *Materials Letters*, 116, 275-277.
4. El-Kassas, H. Y., & El-Sheekh, M. M. (2014). Cytotoxic activity of biosynthesized gold nanoparticles using extract of *Sargassum tenerrimum* against cancer cell lines. *Asian Pacific Journal of Cancer Prevention*, 15(10), 4311-4317.
5. Fawcett, H. J., & Prakash, S. (2020). Algae-mediated green synthesis of metal oxide nanoparticles and their environmental applications. *Journal of Environmental Chemical Engineering*, 8(5), 104258.
6. Guan, X., & Dong, Y. (2019). Enhanced visible-light photocatalytic degradation of organic dyes using Ag/ZnO heterojunction nanocomposites. *Applied Surface Science*, 467, 112-121.
7. Irvani, S. (2011). Green synthesis of metal nanoparticles using plants. *Green Chemistry*, 13(10), 2638-2650.
8. Jayarambabu, N., Kumari, B. S., Rao, K. V., & Prabhu, Y. T. (2014). Beneficial role of zinc oxide nanoparticles on green gram germinating seeds. *International Journal of Multidisciplinary and Current Research*, 2, 282-287.
9. Kasim, N., & Abdullah, A. Z. (2021). Marine macroalgae as a green template for the synthesis of functional materials: A review. *Carbohydrate Polymers*, 258, 117688.
10. Kumar, P., Selvi, A. M., & Govindaraju, K. (2018). Seaweed-mediated synthesis of silver nanoparticles and their antibacterial and photocatalytic properties. *Journal of Photochemistry and Photobiology B: Biology*, 183, 192-200.
11. Li, X., Wang, Z., & Chen, Y. (2017). Plasmonic enhancement of visible-light photocatalysis over Ag/ZnO heterostructures. *ACS Applied Materials & Interfaces*, 9(14), 12450-12458.
12. Madhumitha, G., Elango, G., & Roopan, S. M. (2016). Biotechnology in nanoparticle synthesis: Use of seaweed extracts. *Applied Microbiology and Biotechnology*, 100(2), 501-512.
13. Mohan, S., & Dutta, S. (2019). Degradation of toxic azo and thiazine dyes by advanced oxidation processes: Mechanisms and kinetics. *Chemosphere*, 236, 124350.
14. Nagarajan, S., & Arumugam, M. (2020). Structural and optical characterization of *Sargassum tenerrimum* mediated Ag-ZnO nanocomposites. *Materials Chemistry and Physics*, 251, 123180.
15. Ong, C. B., Ng, L. Y., & Mohammad, A. W. (2018). A review of ZnO nanoparticles as solar photocatalysts: Synthesis, modification and applications. *Journal of Industrial and Engineering Chemistry*, 61, 1-19.
16. Pal, S., Tak, Y. K., & Song, J. M. (2007). Does the antibacterial activity of silver nanoparticles depend on the shape of the nanoparticle? A study of the Gram-negative bacterium *Escherichia coli*. *Applied and Environmental Microbiology*, 73(6), 1712-1720.
17. Prabakaran, E., & Pillay, K. (2021). Nanocomposites of Ag/ZnO for environmental remediation of industrial dye effluents. *Journal of Water Process Engineering*, 40, 101820.
18. Rajeshkumar, S., & Bharath, L. V. (2017). Mechanism of plant-mediated synthesis of silver nanoparticles—A review. *Biocatalysis and Agricultural Biotechnology*, 11, 295-306.
19. Remya, R. R., & Sharma, P. (2019). Green synthesis of metal nanoparticles using brown seaweed *Sargassum* species: Mechanisms and biological applications. *Environmental Chemistry Letters*, 17(3), 1231-1244.
20. Saraswathi, R., & Santhosh, A. (2022). Photocatalytic degradation of Methylene Blue and Reactive dyes using algal-based nanocomposites. *Environmental Nanotechnology, Monitoring & Management*, 17, 100640.
21. Shanmugam, N., & Kannadasan, N. (2016). Marine algae-assisted synthesis of ZnO and Ag-ZnO nanoparticles for environmental cleanup. *Journal of Cleaner Production*, 139, 1021-1030.
22. Sharma, V. K., Yngard, R. A., & Lin, Y. (2009). Silver nanoparticles: Green synthesis and their antimicrobial activities. *Advances in Colloid and Interface Science*, 145(1-2), 83-96.
23. Subash, B., Krishnakumar, B., Swaminathan, M., & Shanthi, M. (2013). Highly efficient visible-light-driven Ag-loaded ZnO photocatalyst for the degradation of Reactive Blue 198. *Materials Science in Semiconductor Processing*, 16(5), 1330-1338.
24. Sundararajan, M., & Gowri, S. (2017). Green synthesis of titanium dioxide nanoparticles using *Sargassum myriocystum* and its photocatalytic degradation of MB dye. *Optik*, 138, 222-229.
25. Tada, H., Suzuki, T., Ito, S., & Akita, T. (2000). Ag-nanoparticle-catalyzed electron transfer in ZnO/Ag/CdS sandwich structures. *The Journal of Physical Chemistry B*, 104(7), 1719-1723.
26. Tripathi, A., & Chung, S. J. (2020). Biopolymer-assisted synthesis of semiconductor heterojunctions for water remediation. *Carbohydrate Polymers*, 242, 116410.
27. Venkatesan, S., & Perumal, P. (2021). Structural and thermal properties of seaweed extract functionalized ZnO nanomaterials. *Thermochimica Acta*, 698, 178880.
28. Verma, R., & Jha, A. K. (2019). Biosynthesis of noble metal nanoparticles and their heterostructures for photocatalytic dye degradation. *Journal of Hazardous Materials*, 378, 120710.
29. Wang, H., & Zhang, L. (2018). Schottky barrier effect in noble metal-decorated semiconductor photocatalysts. *Physical Chemistry Chemical Physics*, 20(18), 12340-12352.

30. Xu, M., & Yang, Q. (2020). Marine polysaccharide-assisted synthesis of functional nanostructures for environmental catalysis. *Marine Drugs*, 18(6), 312.
31. Yadav, A. K., & Srivastava, R. (2021). Mechanistic insights into solar-light driven photocatalytic degradation of toxic organic dyes by Ag/ZnO nanocomposites. *Solar Energy*, 224, 885-897.
32. Yang, J., & Li, D. (2019). Kinetics and mechanism of photocatalytic degradation of cationic and anionic dyes using Ag/ZnO heterostructures. *Applied Catalysis B: Environmental*, 245, 456-467.
33. Zang, Y., & Li, L. (2018). Facile synthesis of surface plasmon resonance enhanced Ag/ZnO heterojunctions for environmental remediation. *Journal of Alloys and Compounds*, 742, 782-791.
34. Zhang, Y., & Chen, C. (2022). Sustainable nanotechnology: Seaweed biopolymers as capping agents for visible light photocatalysts. *ACS Sustainable Chemistry & Engineering*, 10(4), 1420-1432.
35. Zhao, X., & Liu, Y. (2021). Enhanced photocatalytic activity and kinetics of ternary metal-semiconductor-biopolymer composites under visible light. *Chemical Engineering Journal*, 415, 128910.