

Multifunctional B₄C/SnO₂ Nanocomposites: A study on antimicrobial activity, photocatalysis, and electrical properties

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HIGHLIGHTS

- Multifunctional B₄C/SnO₂ nanocomposites (10, 20, 30 %) were synthesized.
- The 30 % SnO₂ composite showed ~98.9 % Rhodamine B degradation under solar light.
- Electrical analysis revealed thermally activated conduction with E_a ~0.84 eV.
- Exhibited moderate antibacterial activity against *E. coli* and *P. aeruginosa*.

ABSTRACT

In this study, a novel B₄C/SnO₂ nanocomposite was synthesized via a facile wet chemical route and comprehensively evaluated for its antimicrobial, photocatalytic, and electrical properties. The 30 % SnO₂-loaded B₄C/SnO₂ nanocomposite exhibited high photocatalytic performance under solar irradiation, achieving ~98 % degradation of Rhodamine B dye within 60 min with an apparent rate constant (k) of 0.04067 min⁻¹. UV-Vis analysis confirmed enhanced visible-light absorption due to interfacial charge transfer between B₄C and SnO₂. In addition, the B₄C/SnO₂ nanocomposite demonstrated significant antibacterial activity against Gram-negative bacteria with inhibition zones of 12–20 mm and showing MIC values of 300.85, 244.46, and 178.6 µg/mL against *E. coli*, and 235.95, 194.34, and 113.06 µg/mL against *P. aeruginosa* for the 10 %, 20 %, and 30 % SnO₂ loadings, respectively. Attributed to the generation of reactive oxygen species and direct interaction with bacterial cell walls. Electrical conductivity measurements indicated thermally activated conduction behavior, with an activation energy of 0.84 eV, confirming the high-resistivity semiconducting nature of the B₄C/SnO₂ composite and its potential relevance for temperature-sensitive and resistive sensing applications. The synergistic interaction between B₄C and SnO₂ contributes to the multifunctionality of the composite, highlighting its potential in environmental remediation, antimicrobial coatings, and electronic applications.

1. Introduction

The increasing demand for multifunctional materials capable of addressing environmental, biomedical, and electronic challenges has sparked interest in designing composite nanomaterials with enhanced and tunable properties. Recent reports have highlighted the importance of tailoring band gap engineering, heterojunction architecture, and microstructure control to achieve multifunctional behaviour in composite materials [1–4]. Among various candidates, boron carbide (B₄C) and tin oxide (SnO₂) have emerged as promising components due to

their unique physical, chemical, and electronic characteristics. B₄C, a robust p-type semiconductor with a moderate band gap (~1.5–2.6 eV), is well-known for its high hardness, thermal stability, and chemical inertness, making it a suitable material for various advanced applications [5,6]. On the other hand, SnO₂, an n-type semiconductor with a wide band gap (~3.6 eV), exhibits excellent optical and electronic properties but suffers from limitations such as charge recombination and particle agglomeration when used alone in photocatalysis or sensing [7, 8]. In this context, the synthesis of B₄C/SnO₂ nanocomposites aims to combine the complementary features of both materials, thereby

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improving their overall performance in applications ranging from environmental remediation to antimicrobial action and electrical sensing [9,10].

Environmental contamination is caused by the extensive use of organic dyes in wastewater from industries including paper, clothing, and textile production. The substances found in the dye effluents are extremely dangerous and carcinogenic, and they might pose significant risks human health [11]. Even at low concentrations (less than 1 ppm), these dyes are highly toxic to aquatic ecosystems. Therefore, removing organic dyes from industrial effluents is both critical and necessary. Traditional methods for treating industrial wastewater, such as adsorption and coagulation, are commonly used to eliminate these dyes [12,13]. However, since dyes are organic pollutants, these processes often generate toxic byproducts, necessitating additional measures to address the problem of secondary pollution [13,14]. Photocatalysis has gained attention as a green and cost-effective strategy for degrading organic pollutants such as industrial dyes, which are persistent, carcinogenic, and difficult to treat using conventional methods [15,16]. Recent studies have demonstrated that constructing heterojunctions such as TiO_2 and $\text{g-C}_3\text{N}_4$ -based nanocomposites can significantly enhance visible-light absorption and charge carrier separation, leading to superior photocatalytic efficiency [17,18]. The interface between B_4C and SnO_2 can facilitate efficient charge transfer, suppress recombination of photoinduced carriers, and enhance electron mobility, leading to improved photocatalytic activity under visible light irradiation. Previous studies have reported $\text{B}_4\text{C}/\text{SnO}_2$ composites primarily for photocatalytic applications; however, their conductivity, biocompatibility and cytotoxic behavior have not been explored in detail [19].

Beyond photocatalysis, the generation of reactive oxygen species (ROS) during light-induced processes also imparts antibacterial properties to the material [20]. This makes $\text{B}_4\text{C}/\text{SnO}_2$ nanocomposites attractive for applications in water purification where both chemical and biological contaminants must be addressed simultaneously. The working hypothesis is that incorporating SnO_2 into B_4C will modify the surface chemistry and interaction with biological systems, potentially enhancing reactive oxygen species (ROS) generation at higher doses but maintaining good biocompatibility at environmentally relevant concentrations. Furthermore, to explore the material's potential in electronic and sensor devices, temperature-dependent current–voltage (I–V) studies were carried out. These measurements provide insight into the charge transport mechanism, activation energy, and the influence of temperature on electrical conductivity—important parameters for device integration [21].

The novelty of this study lies in the comprehensive evaluation of $\text{B}_4\text{C}/\text{SnO}_2$ nanocomposites as a multifunctional material, demonstrating simultaneous photocatalytic degradation of Rhodamine B, antimicrobial activity against *Escherichia coli* (*E. coli*) and *Pseudomonas aeruginosa* (*P. aeruginosa*), and thermally activated electrical behavior. The objective of this study is to synthesize $\text{B}_4\text{C}/\text{SnO}_2$ nanocomposites via a simple wet chemical route and evaluate their structural, optical, and functional characteristics, emphasizing their performance in solar-driven dye degradation, antibacterial activity, and thermally activated electrical conductivity. By integrating these diverse functional properties, the present work highlights the potential of $\text{B}_4\text{C}/\text{SnO}_2$ nanocomposites in next-generation environmental, biomedical, and electronic applications.

2. Experimental details

2.1. Materials

Boric acid (H_3BO_3 , 99.9 %), acetone, activated magnesium (Mg, 98 %), dimethyl sulfoxide (DMSO), tin(II) chloride (SnCl_2), and hydrochloric acid (HCl) were purchased from Sigma-Aldrich, India. Mueller-Hinton Agar, Mueller-Hinton Broth from HiMEDIA, India. Both strains were bought from the Chandigarh, India-based Institute of Microbial Technology (IMTECH) and Microbial Type Culture Collection &

Gene Bank (MTCC). Human embryonic kidney cell line (HEK-293) was obtained from National Centre for Cell Science (NCCS) Pune.

2.2. Synthesis of $\text{B}_4\text{C}/\text{SnO}_2$ nanocomposites

B_4C nanoparticles were successfully synthesized using the solvothermal method as described by Singh et al. [22] with the key parameters as follows: boric acid (H_3BO_3), activated magnesium, and acetone were used as precursors in a 50 mL autoclave and the sealed autoclave was heated at 700 °C to obtain the B_4C powder. $\text{B}_4\text{C}/\text{SnO}_2$ nanocomposite with SnO_2 composition of 10 %, 20 % and 30 % was then prepared via a reflux approach [19]. In this process, freshly prepared aqueous solutions of SnCl_2 , B_4C , and HCl were poured into a magnetically stirred round-bottom flask and refluxed at 100 °C until precipitation formed. The mixture was then cooled to room temperature and washed repeatedly with distilled water until reaching neutral pH. The purified precipitate was finally collected and vacuum-dried at 80 °C for 7 h.

2.3. Characterization of $\text{B}_4\text{C}/\text{SnO}_2$ nanocomposites

A UV–visible UV-1800 (Shimadzu UV spectro-photometer, Japan) was used to analyze optical absorption spectra of the dried $\text{B}_4\text{C}/\text{SnO}_2$ composite powder. The morphology and structure were analyzed by TEM JEOL 2100F, while size and anatomy were determined by SEM (Zeiss EVO40). The Varian 7000 FTIR was used to do the Fourier Transform Infrared (FTIR) analysis in the 4000–400 cm^{-1} range, in order to identify the functional groups.

2.4. Antibacterial assay

2.4.1. Test organisms

Escherichia coli (DH5 α), a gram-negative strain, and *Pseudomonas aeruginosa* (MTCC 1035), a gram-negative MDR strain, were sub cultured and kept at –80 °C in nutritional broth and nutrient agar media. Fresh bacterial strains were cultivated and kept in Mueller-Hinton Broth for 18 h at 37 °C before to the test.

2.4.2. Minimum inhibitory concentration (MIC)

Using the traditional broth dilution method (CLSI M07-A8), the antibacterial activity of $\text{B}_4\text{C}/\text{SnO}_2$ nanocomposites was examined by evaluating the observable growth of microorganisms in the agar broth [23]. They were serially diluted twice at concentrations ranging from 200 $\mu\text{g}/\text{ml}$ to 0.391 mg/ml with an adjusted bacterial concentration (1.5×10^8 CFU/ml, 0.5 McFarland's standard) in order to determine the minimum inhibitory concentration (MIC) in Mueller-Hinton broth. The control was incubated for 24 h at 37 °C using just inoculation broth. The turbidity of the tubes was measured before and after incubation in order to confirm the MIC value. All MIC results are reported as mean $\pm$ standard deviation (SD) based on triplicate measurements ($n = 3$).

For MBC, 50 μl aliquots from each tube that showed no detectable bacterial growth, were put into Mueller-Hinton broth and incubated for 24 h at 37 °C after MIC analysis of the $\text{B}_4\text{C}/\text{SnO}_2$ nanocomposites. When 99.9 % of the bacterial population is eradicated at the lowest dose of an antibiotic substance, this is referred to as the MBC endpoint. This was achieved by examining broth tubes both before and after incubation to see whether bacteria were present. MBC values are also reported as mean $\pm$ SD ($n = 3$) to ensure reproducibility and statistical reliability.

2.4.3. Disc diffusion assay

The bacterial strains' pure cultures were sub cultured on Mueller-Hinton Broth at 37 °C for the duration of the night. The turbidity of the bacterial culture was raised to 0.5 McFarland (1.5×10^8 CFU/mL). Each bacterial strain was uniformly swabbed onto separate Mueller-Hinton agar plates using sterile cotton swabs under sterile circumstances. Wells of an 8 mm diameter were made by punching wells onto

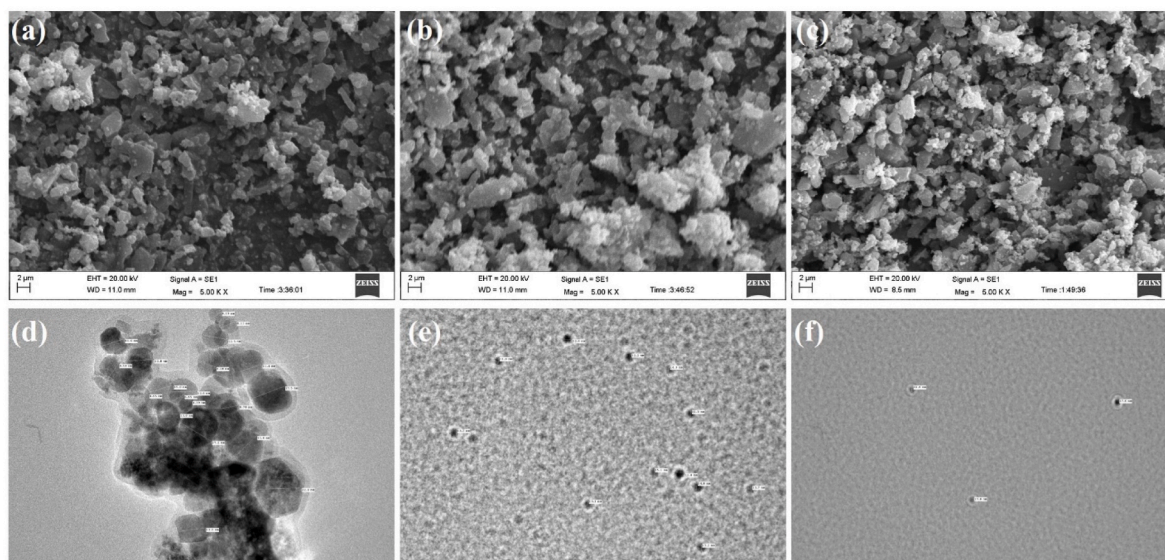


Fig. 1. (A–C) SEM micrographs; (d–f) TEM images of B_4C/SnO_2 nanocomposites with varying SnO_2 content: 10 %, 20 %, and 30 % respectively.

agar plates with a sterile cork borer and then removing the agar. Following that, 100 μ L of B_4C/SnO_2 nanocomposites were added to each well at sub-MIC concentrations, which were selected as approximately one-half of the MIC value for each nanocomposite (w/v) to ensure adequate diffusion and measurable inhibition. After a 24-h incubation period at 35 $^{\circ}C$ –37 $^{\circ}C$, the zones of inhibition surrounding the wells were measured in millimeters using a caliper [24].

2.4.4. Cytotoxicity assay

The cytotoxicity of the synthesized nanocomposites against HEK-293 cells was assessed. HEK-293 cell lines, which were obtained from NCCS Pune, were maintained in DMEM medium. The cells were treated with various concentrations of the synthesized nanocomposites (10, 20, 40, 80, and 160 μ g/ml) for 24 h. Subsequently, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT 1 mg/mL) was added, and the cells were incubated for an additional 4 h in a CO_2 incubator at 37 $^{\circ}C$. The absorbance at 595 nm was measured using the Bio-Rad, iMark- Microplate reader. Cell viability (%) was calculated relative to the untreated control group, which was considered 100 % viability. For the various concentrations of B_4C/SnO_2 nanocomposites, the level of cytotoxicity was assessed.

2.5. Photocatalytic activity measurement

The aqueous solution of the textile dye Rhodamine B (RhB) was used to assess the photocatalytic activities of 30 % B_4C/SnO_2 nanocomposite. The 100 ppm RhB stock solution was prepared by dissolving 50 mg of RhB in 500 mL of distilled water (equivalent to 100 mg/L or 100 ppm). The photocatalytic experiments were conducted under natural sunlight at Jawaharlal Nehru University, New Delhi, India, during the month of April, between 10:00 a.m. and 2:30 p.m., corresponding to the period of maximum solar intensity. The concentration of the dyes was constant, causing variations in the concentration of the nanocomposite sample (i. e. 0, 50, 100 ppm) where ppm denotes mg of catalyst per liter of reaction mixture. As a control, the 0 (ppm) parts per million included 1 ml of dye and 8 ml of water, but with no nanocomposites. Every experiment was conducted at room temperature. After 30 min of dark magnetic stirring to achieve the adsorption–desorption equilibrium, the aqueous solutions were exposed to sunlight. After a predetermined amount of time (0, 20, 40, 60 min), analytical samples were extracted from reaction systems and centrifuged to separate the photocatalyst prior to analysis. Using a UV–visible spectrophotometer, the variations in absorption strength in

spectra were examined.

2.6. I–V characteristics study of B_4C/SnO_2 nanocomposite film

To study the electrical behavior of B_4C/SnO_2 nanocomposites, thin films were prepared using a solution-based spin coating method. A homogeneous dispersion was obtained by sonicating 3 mg of B_4C/SnO_2 (30 %) composite powder in 1 mL of ethanol for 10–15 min. Prior to deposition, glass substrates were thoroughly cleaned and thermally dried in a furnace at 70 $^{\circ}C$ to remove residual moisture and contaminants. The prepared solution was then deposited onto the glass substrates using a spin coater operating at 2500 rpm. The resulting films were further annealed in a furnace at 70 $^{\circ}C$ for 3 h to improve film adhesion and remove any residual solvent. The current–voltage (I–V) characteristics of the B_4C/SnO_2 thin films were recorded using Keithley source meter. Silver paste was applied on the thin films to ensure ohmic contacts and stable electrical connections for measurements. I–V measurements were performed under a temperature-controlled environment to investigate the temperature dependence (up to 463K) of electrical conductivity.

3. Results and discussion

3.1. Characterization of B_4C/SnO_2 nanocomposites

Fig. 1(a–c) present the SEM images of B_4C/SnO_2 nanocomposites with increasing SnO_2 content (10 %, 20 %, and 30 %, respectively). The surface morphology reveals agglomerated, irregular particles distributed, suggesting successful integration of SnO_2 within the B_4C matrix. In Fig. 1(a), the composite with lower SnO_2 content shows a relatively dense and compact granular surface. As seen in Fig. 1(b), the intermediate SnO_2 concentration results in a more porous structure, possibly due to increased oxide content disrupting grain connectivity. Fig. 1(c), with the highest SnO_2 loading, shows enhanced particle definition and reduced aggregation, implying better dispersion of SnO_2 nanoparticles within the B_4C matrix. In Fig. 1(d–f), TEM analysis further confirms the presence of nanocrystalline SnO_2 particles (10–40 nm) embedded within the B_4C matrix. The homogenous distribution and reduced agglomeration of SnO_2 with increasing content suggest strong interfacial interactions, which can significantly influence the material's photocatalytic, electrical, and antimicrobial behavior.

FTIR spectroscopy was employed to identify the functional groups

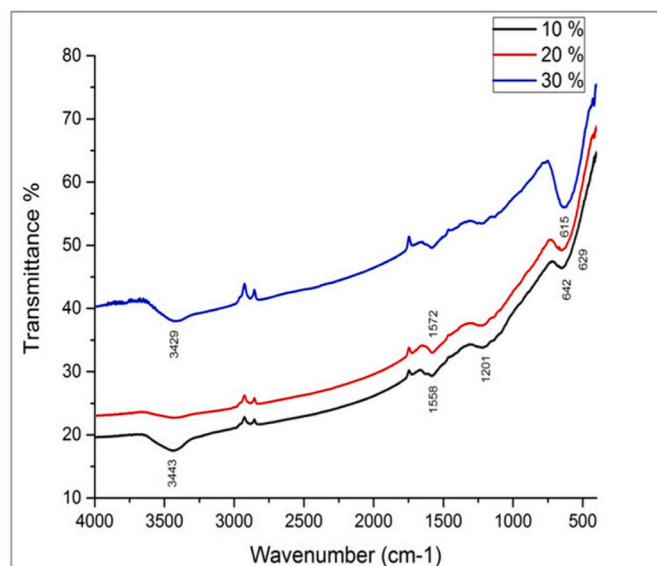


Fig. 2. FTIR spectra of B_4C/SnO_2 nanocomposites with varying SnO_2 content: 10 %, 20 %, and 30 %.

Table 1

Minimum Inhibitory Concentration (MIC) and Minimum Bactericidal Concentration (MBC) for B_4C/SnO_2 nanocomposite against *P. aeruginosa* and *E. coli*.

Bacterial strains	B_4C/SnO_2 (10 %) S1		B_4C/SnO_2 (20 %) S2		B_4C/SnO_2 (30 %) S3	
	MIC ($\mu g/ml$)	MBC ($\mu g/ml$)	MIC ($\mu g/ml$)	MBC ($\mu g/ml$)	MIC ($\mu g/ml$)	MBC ($\mu g/ml$)
<i>P. aeruginosa</i>	300.85	601.7	244.46	488.92	178.6	357.2
<i>E. coli</i>	235.95	471.9	194.34	388.68	113.06	226.12

and bonding characteristics in B_4C/SnO_2 nanocomposites with varying SnO_2 content (10 %, 20 %, and 30 %). As shown in Fig. 2, all samples exhibit a broad absorption band around $3443\text{--}3429\text{ cm}^{-1}$, corresponding to O–H stretching vibrations, likely due to surface hydroxyl groups [25,26]. The slight shift in this band with increasing SnO_2 concentration suggests variation in surface interaction and hydration. Bands observed around $1572\text{--}1558\text{ cm}^{-1}$ can be attributed to H–O–H bending vibrations, confirming the presence of molecular water or possibly surface carbonates [27]. The peak at $\sim 1201\text{ cm}^{-1}$ is assigned to B–C stretching vibrations, indicative of the B_4C network. The persistence of this peak across all compositions confirms the structural presence of B_4C in the composite matrix [5]. The FTIR spectrum shows characteristic Sn–O–Sn stretching vibrations at $\sim 642, 629, \text{ and } 615\text{ cm}^{-1}$. However, due to the interfacial interaction between B_4C and SnO_2 , overlapping contributions from B–C–B and B–O bending modes in this region cannot be ruled out, as reported in similar oxide-carbide systems [28,29]. The overall increase in transmittance with SnO_2 loading implies improved dispersion and reduced absorbance, which may influence photocatalytic or antimicrobial behavior. Fig. S1 displays the UV–Vis absorbance spectra of B_4C/SnO_2 composites with 10 %, 20 %, and 30 % SnO_2 . A dominant absorption feature centered at $\sim 270.6\text{ nm}$ is observed and is attributed to electronic transitions intrinsic to boron carbide [30]. A weaker feature near $\sim 360\text{--}370\text{ nm}$ is evident and can be ascribed to SnO_2 -related transitions or surface states [31,32]. Increasing SnO_2 content leads to a progressive rise in overall absorbance and an extended absorption tail into the near-visible region. This trend indicates enhanced photon harvesting and increased defect/surface-state absorption in the composites, which likely improves charge separation at the $B_4C\text{--}SnO_2$ interface. Based on its optical response, the 30 % B_4C/SnO_2 composite

Table 2

Zone of Inhibition (ZIC) measured for antibacterial activity of the synthesized B_4C/SnO_2 nanocomposites against *P. aeruginosa* and *E. coli*.

Microorganisms	B_4C/SnO_2 10 %	B_4C/SnO_2 20 %	B_4C/SnO_2 30 %	+ve Control (Gentamicin)	-ve Control (DW)
<i>P. aeruginosa</i>	12 mm	15 mm	20 mm	29 mm	0
<i>E. coli</i>	10 mm	12 mm	14 mm	20 mm	0

was selected for subsequent photocatalytic studies.

3.2. Antimicrobial activity of B_4C/SnO_2 nanocomposites

The results of the minimum inhibitory concentration (MIC) & minimum bactericidal concentration (MBC) of B_4C/SnO_2 (10 %, 20 %, 30 %) for the two pathogenic strains are shown in Table 1. The MBC is the amount of an antibacterial agent required to kill nearly all of the microorganisms, whereas the MIC is the lowest amount of an antimicrobial agent required to sufficiently impede the growth of the pathogen under investigation. The MIC values for B_4C/SnO_2 10 %, B_4C/SnO_2 20 %, & B_4C/SnO_2 30 % were found to be $300.85\text{ }\mu g/ml$, $244.46\text{ }\mu g/ml$, & $178.6\text{ }\mu g/ml$ respectively against *E. coli* and $235.95\text{ }\mu g/ml$, $194.34\text{ }\mu g/ml$, & $113.06\text{ }\mu g/ml$ against *P. aeruginosa*. Overall, the MIC and MBC test findings show that B_4C/SnO_2 nanocomposites have the potential to be antibacterial agents against *E. coli* and *P. aeruginosa* pathogens.

3.2.1. Zone of inhibition

The antibacterial activity of the synthesized B_4C/SnO_2 nanocomposites was further assessed using the agar well diffusion method, with the zone of inhibition (ZOI) measured against *P. aeruginosa* and *E. coli*. This qualitative assay provides insight into the ability of the nanocomposites to diffuse through agar media and inhibit bacterial growth in a concentration-dependent manner. As summarized in Table 2, the zone of inhibition increased with higher SnO_2 content in the composite. Against *P. aeruginosa*, the ZOI measured 12 mm, 15 mm, and 20 mm for B_4C/SnO_2 at 10 %, 20 %, and 30 %, respectively. Similarly, for *E. coli*, inhibition zones of 10 mm, 12 mm, and 14 mm were observed (Fig. 3). Here Gentamicin was considered as the positive control whereas distilled water for negative control as the nanocomposites were dissolved in it. In comparison, the positive control (Gentamicin) produced significantly larger inhibition zones of 29 mm for *P. aeruginosa* and 20 mm for *E. coli*, while no inhibition was observed in the negative control.

The increasing antibacterial effect with higher SnO_2 content may be possible due to the enhanced generation of reactive oxygen species (ROS), which can induce oxidative stress in bacterial cells, leading to membrane damage and cell death. Furthermore, the nanoscale nature of the composites likely facilitates penetration and interaction with bacterial membranes, disrupting normal cellular function. These results reinforce the findings from the MIC and MBC assays, confirming that B_4C/SnO_2 nanocomposites, particularly the 30 % B_4C variant, possess significant antibacterial activity. The synergy between B_4C and SnO_2 enhances the overall antimicrobial efficiency, making these materials promising candidates for dual-action wastewater treatment systems that target both chemical and biological contaminants.

3.2.2. Cytotoxicity assay

The cytotoxicity assay (MTT) was performed on HEK-293 cell lines to evaluate the biocompatibility of nanoparticles. The assay aimed to determine the potential cytotoxic effects of the nanocomposites across a range of concentrations over a 24-h exposure period. As shown in Fig. 4, the B_4C/SnO_2 NCs exhibited a clear dose-dependent reduction in cell viability, indicating that cytotoxicity increased with increasing concentrations of the nanocomposites. Each data point represents the mean $\pm$ standard deviation ($n = 3$) obtained from triplicate measurements. The very small standard deviations (0.03–0.15), reflect good consistency

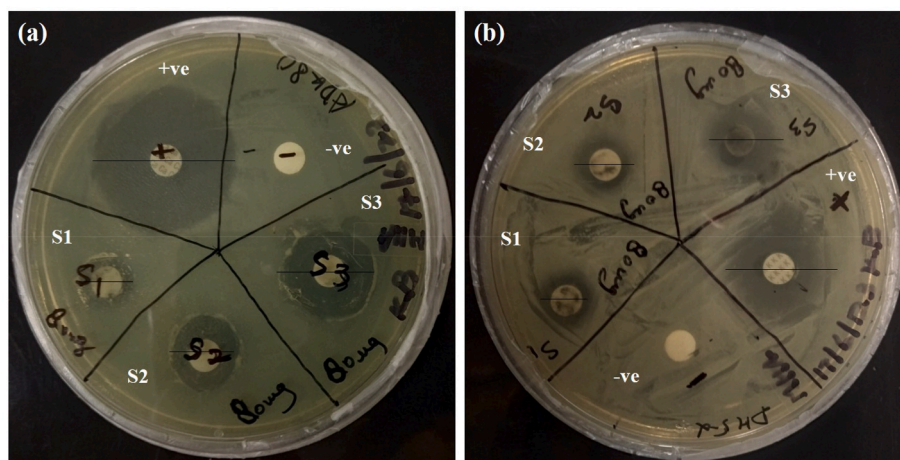


Fig. 3. Antibacterial potential of B_4C/SnO_2 nanocomposite against (a) *P. Aeruginosa*, (b) *E. Coli* showing inhibition zones.

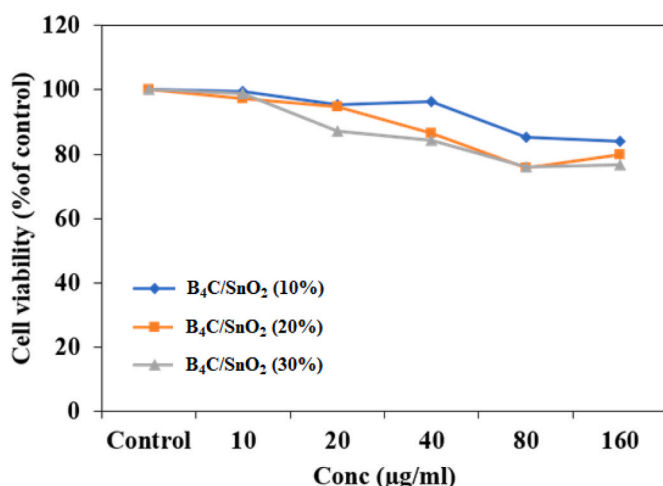


Fig. 4. Cell viability percentage of HEK-293 cells treated with B_4C/SnO_2 nanocomposite.

among the technical replicates. As the concentration increased from 10 to 160 $\mu\text{g/mL}$, a gradual decrease in cell viability was observed for all samples, indicating a mild dose-dependent cytotoxic response. Statistical analysis using one-way ANOVA revealed significant variation ($p < 0.05$) in cell viability among the B_4C/SnO_2 composites with different SnO_2 loadings at all tested concentrations. The calculated half-maximal inhibitory concentration (IC_{50}) values of B_4C/SnO_2 (10 %, 20 %, 30 %), were 459, 343 and 311 $\mu\text{g/mL}$ respectively. These results suggest that while the nanocomposites exhibit some level of cytotoxicity at higher concentrations, they are relatively non-toxic at lower doses, particularly within the range relevant for environmental applications. This shows that these nanocomposites exhibit dose-dependent cytotoxicity with potential safe margins at lower concentration and can be used for water treatment applications where minimal direct human exposure is expected. Notably, the increase in composite content slightly enhanced the cytotoxic response, potentially due to greater interaction of the particles with cellular components at higher loadings. However, further comprehensive toxicological evaluations using additional cell lines, Gram-positive bacterial species, long-term exposure studies, and complementary assays are essential to fully establish their biosafety profile. Overall, the MTT assay and IC_{50} calculations provide valuable insights into the cytotoxicity of B_4C/SnO_2 nanocomposites, contributing to the development of safe and effective nanomaterials for environmental remediation.

3.3. Photocatalytic activity

The photocatalytic performance of the synthesized B_4C/SnO_2 (30 %) nanocomposite was assessed by evaluating the degradation of Rhodamine B (RhB) dye under natural sunlight irradiation. The photocatalytic experiments were conducted under natural sunlight at Jawaharlal Nehru University, New Delhi, India, during the month of April, between 10:00 a.m. and 2:30 p.m., corresponding to the period of maximum solar intensity. To study the effect of catalyst loading on photocatalytic efficiency, different concentrations of B_4C/SnO_2 nanocomposite (0 ppm, 50 ppm, and 100 ppm) were introduced into RhB aqueous solutions. The degradation efficiency was determined by monitoring the decrease in absorbance at the characteristic wavelength of RhB ($\lambda_{\text{max}} = 554 \text{ nm}$) using UV-Visible spectroscopy at various time intervals (0, 20, 40, and 60 min).

The following formula was used to determine a dye's degradation efficiency based on changes in RhB concentrations [33]:

$$\text{Degradation percentage (\%)} = \frac{C_0 - C_t}{C_0} \times 100$$

where the dye concentrations prior to and following that reaction were denoted by C_0 and C_t .

Fig. 5(a–c) demonstrate a progressive decrease in RhB absorbance intensity with increasing irradiation time, confirming effective photo-degradation. Among all samples, the 30 % B_4C/SnO_2 nanocomposite exhibited the highest photocatalytic efficiency, achieving 98.9 % RhB degradation within 60 min at a catalyst concentration of 100 ppm. Fig. 5 (d) shows the corresponding kinetic trend which further validates the improved photocatalytic activity with increased catalyst concentration. The photocatalytic performance is attributed to the synergistic effect of B_4C and SnO_2 , where B_4C enhances electron transfer and inhibits electron-hole recombination, while SnO_2 facilitates visible-light harvesting and reactive oxygen species (ROS) generation.

Fig. S2 illustrates the kinetic analysis of Rhodamine B (RhB) photo-degradation, where a linear variation between $\ln(C_0/C_t)$ and irradiation time was obtained. This linearity confirms that the degradation process follows pseudo-first-order kinetics. The apparent rate constant (k) was determined from the slope of the linear plot based on the Langmuir-Hinshelwood model, expressed as [34]:

$$\ln\left(\frac{C_0}{C_t}\right) = kt$$

Here, C_0 and C_t correspond to the RhB concentrations at the initial time and after illumination time t , respectively. The calculated k value of 0.04067 min^{-1} and a high correlation coefficient ($R^2 > 0.9$) validate the

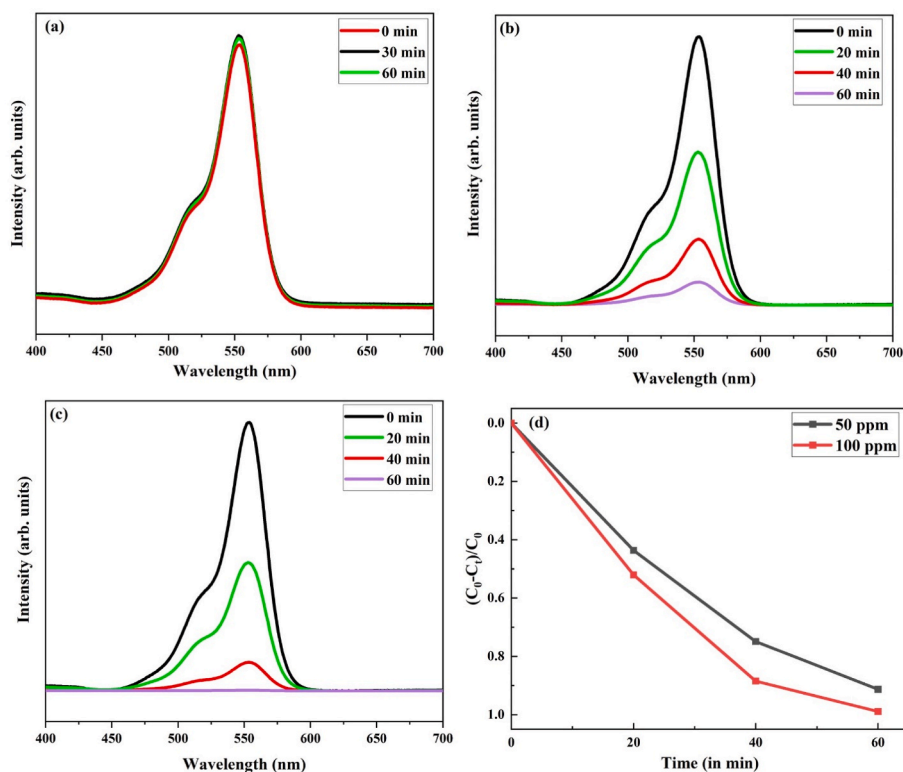


Fig. 5. (A–c) Photodegradation plot of Rhodamine B dye (100 ppm) aqueous solution in presence of $\text{B}_4\text{C}/\text{SnO}_2$ (30 %) catalyst loading (a) 0 ppm (b) 50 ppm (c) 100 ppm; (d) Photocatalytic degradation efficiency of $\text{B}_4\text{C}/\text{SnO}_2$ nanocomposite.

Table 3

Summary of various photocatalyst supports and their corresponding photocatalytic performances.

Material Photocatalyst	Dye	Degradation%, time, source	[Ref.]
SnO_2 nanocrystals	RhB	91.7 %, 120 min, UV–visible irradiation	[37]
SnO_2 NPs	Methylene Blue (MB)	93 %, 240 min, UV irradiation	[38]
SnO_2 NPs	RY186	90 %, 180 min, sunlight	[39]
B_4C	MB	76.04 %, 60 min, UV–visible irradiation	[40]
$\text{B}_4\text{C}/\text{SnO}_2$ (50 %)	MB	79.41 %, 20 min, UV–visible irradiation	[19]
$\text{SnO}_2/\text{MoO}_3$ nanocomposite	MB	73.0 %, 150 min, sunlight	[41]
SnO_2/CuO	MB	92 %, 30 min, visible light	[42]
TiO_2/rGO	RhB	98.8 %, 20 Min, UV light	[43]
$\text{MnO}_2/\text{g-C}_3\text{N}_4$	MB	89 %, 120 min, visible light irradiation	[44]
$\text{C}_3\text{N}_4/\text{rGO}/\text{SnO}_2$	RhB	83.2 %, 120 min, visible light irradiation	[45]
$\text{B}_4\text{C}/\text{SnO}_2$ (30 %)	RhB	98 %, 60 min, sunlight	This work

reliability of the kinetic fit. The relatively high rate constant value suggests efficient separation and migration of photogenerated charge carriers within the $\text{B}_4\text{C}/\text{SnO}_2$ heterostructure, enabling rapid RhB degradation under light exposure. Upon exposure to sunlight, SnO_2 absorbs photons with energy equal to or greater than its band gap, leading to the excitation of electrons from the valence band (VB) to the conduction band (CB), thereby generating electron–hole pairs. The presence of B_4C , with its high surface area, facilitates the rapid migration of photogenerated electrons from SnO_2 to B_4C , effectively reducing electron–hole recombination. This charge separation process prolongs the lifetime of the charge carriers and enhances the photocatalytic

efficiency.

The photogenerated electrons transferred to the B_4C surface react with dissolved oxygen molecules (O_2) in the aqueous solution to produce superoxide radicals. Simultaneously, the photogenerated holes in the VB of SnO_2 can oxidize surface-adsorbed water molecules (H_2O) or hydroxide ions (OH^-) to form highly reactive hydroxyl radicals ($\cdot\text{OH}$). Both superoxide and hydroxyl radicals are potent oxidizing agents capable of breaking down Rhodamine B dye molecules into smaller, non-toxic compounds such as CO_2 and H_2O . Thus, the $\text{B}_4\text{C}/\text{SnO}_2$ heterostructure promotes an efficient Z-scheme-like charge transfer pathway, where B_4C acts as an electron mediator, thereby enhancing the overall photocatalytic activity. This proposed mechanism aligns with previous reports on heterojunction photocatalysts such as CdS-TiO_2 and $\text{g-C}_3\text{N}_4/\text{rGO}/\text{MoS}_2$ and composites, which demonstrated enhanced charge transfer and reactive oxygen species generation through similar interfacial electron migration pathways [18,35,36]. A comparative overview of recent photocatalyst support systems reported in the literature is presented in Table 3, highlighting the photocatalytic efficiencies. The stability and recyclability of the $\text{B}_4\text{C}/\text{SnO}_2$ (30 %) photocatalyst were examined for five consecutive RhB degradation cycles under identical experimental conditions (Fig. S3). The catalyst retained 94.91 % of its initial photocatalytic efficiency after five cycles, with only a marginal decrease from 98.9 % in the first run. This minimal decline can be attributed to slight photocatalyst loss during recovery and washing. The results confirm the significantly enhanced stability, reusability, and durability of the $\text{B}_4\text{C}/\text{SnO}_2$ composite compared to literature-reported SnO_2 -based systems, highlighting its promise for sustainable wastewater treatment applications.

3.4. Conduction and material behavior

The electrical behavior of $\text{B}_4\text{C}/\text{SnO}_2$ nanocomposite thin films was investigated through temperature-dependent current–voltage (I–V) measurements conducted over a temperature range of 298–463 K. The

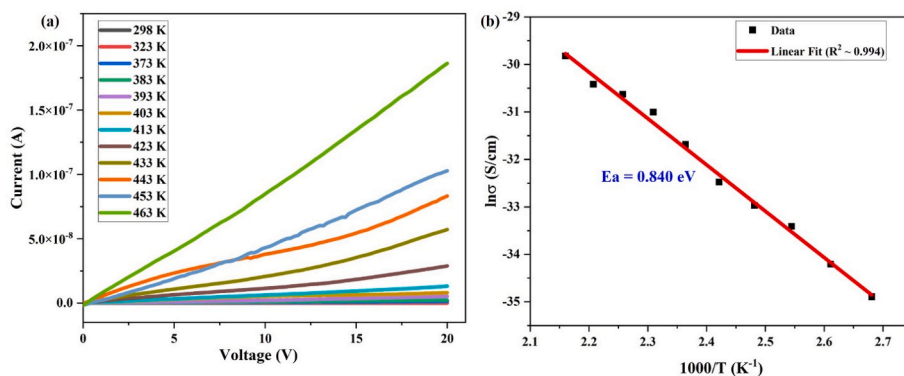


Fig. 6. (A) I–V plot; (b) Arrhenius plot of B₄C/SnO₂ (30 %) nanocomposites.

I–V curves revealed a clear increase in current with rising temperature, indicating a thermally activated conduction mechanism as shown in Fig. 6(a). This behavior is characteristic of semiconducting materials where the charge carrier density increases as thermal energy assists carriers in overcoming the energy barrier for conduction. To further quantify the conduction mechanism, the electrical conductivity (σ) was calculated. The conductivity increased from $\sim 10^{-17}$ to 10^{-13} S/cm over the studied temperature range, confirming the high-resistivity nature of the composite at room temperature and the enhancement of charge transport at elevated temperatures. The temperature dependence of conductivity was analyzed using the Arrhenius relation [46]:

$$\sigma = \sigma_0 \exp(-E_a / kT)$$

where σ_0 is a constant, E_a is the activation energy, and k is the Boltzmann's constant. $\ln(\sigma)$ versus $1000/T$ exhibited excellent linearity ($R^2 \approx 0.994$), indicating that the conduction process is governed by thermally activated hopping or band conduction. From the slope of the linear fit, the activation energy E_a was calculated to be 0.840 eV (Fig. 6 (b)). This moderately high activation energy suggests the presence of deep trap states or barriers at grain boundaries that hinder carrier mobility, which is typical in oxide-carbide nanocomposites [47]. The interfaces between B₄C and SnO₂ nanoparticles introduce potential barriers and trap states that localize charge carriers, while grain boundaries further hinder their mobility, resulting in high resistivity. The observed behavior reflects the composite's semiconducting character, with low intrinsic conductivity at ambient conditions that improves significantly with thermal excitation. As temperature increases, thermal energy assists carriers in overcoming these barriers, enhancing conductivity. Such grain boundary and trap-controlled hopping transport is common in disordered or nanostructured semiconductors and plays a crucial role in determining the sensitivity and stability of resistive-type sensors. Although the absolute conductivity values are relatively low in B₄C/SnO₂ nanocomposite compared to benchmark oxide semiconductors, such high-resistivity behavior is advantageous for resistive-type sensing and temperature-dependent switching devices where small current variations are desirable for signal amplification [48, 49].

The combination of a wide band gap metal oxide (SnO₂) with a semiconducting carbide (B₄C) result in a composite material with improved stability and tunable electronic properties. SnO₂, though a well-known n-type semiconductor, often suffers from rapid electron-hole recombination and poor conductivity due to particle agglomeration. Incorporation with B₄C introduces additional pathways for charge separation and transport due to its covalent bonding structure and moderate band gap. However, the poor conductivity at room temperature indicates limited carrier mobility in the composite unless thermally excited. The linearity in the Arrhenius plot and the gradual increase in conductivity with temperature support the semiconducting nature of the nanocomposite. These properties make B₄C/SnO₂ a potential candidate

for applications in temperature-responsive electronic devices, sensors, and photocatalysts, where controlled conductivity is desired.

4. Conclusion

A multifunctional B₄C/SnO₂ nanocomposite was successfully developed and evaluated for its photocatalytic, antimicrobial, and electrical performance. The material showed high photocatalytic degradation of Rhodamine B (98.9 % in 60 min) under solar irradiation, supported by enhanced light absorption and charge carrier dynamics. Antibacterial studies confirmed its effectiveness against Gram-negative strains, likely due to ROS generation and cell wall interaction. Electrical measurements revealed thermally activated conduction ($E_a \sim 0.840$ eV), indicating the presence of defect-mediated mechanisms. The integration of conductive B₄C with semiconducting SnO₂ provided a synergistic enhancement of properties, making the nanocomposite a promising candidate for diverse applications in water treatment, microbial resistance, and sensing devices. Future research should therefore focus on optimizing the B₄C/SnO₂ interface, evaluating performance under realistic environmental conditions, integrating the material into prototype resistive sensors, and examining its applicability in broader water purification and antimicrobial technologies. Overall, this study establishes B₄C/SnO₂ as a promising multifunctional platform while identifying clear pathways for advancing it toward practical applications.

CRedit authorship contribution statement

Kanika Baru: Writing – original draft, Methodology, Investigation, Data curation. **Manjot Kaur:** Writing – review & editing, Supervision, Software, Formal analysis. **Kajal Kumari:** Visualization, Supervision, Resources, Formal analysis. **Nijamuddin Ansari:** Methodology, Investigation. **Atul Tiwari:** Software, Resources. **Akshay Kumar:** Writing – review & editing, Resources. **Ramovatar Meena:** Writing – review & editing, Funding acquisition, Conceptualization.

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Declaration of competing interest

There are no competing interests, according to the authors.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.matchemphys.2025.131942>.

Data availability

Data will be made available on request.

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