

Effective photocatalytic degradation of sulfamethoxazole using PAN/SrTiO₃ nanofibers

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ABSTRACT

Freshwater scarcity driven by pollution and climate change necessitates the development of effective water purification methods. There is an urgent need for innovative solutions that can efficiently remove contaminants from water sources. A effective material for the photocatalytic degradation of organic sulfonamide antibiotics from water was developed in this study. A composite of electrospun strontium titanate (SrTiO₃) and carbon fibers polyacrylonitrile/strontium titanate (PAN/SrTiO₃) was employed for the photocatalytic degradation of sulfamethoxazole (SMX). Scanning Electron Microscopy/Energy Dispersive Spectroscopy (SEM-EDS), Transmission electron microscopy (TEM), X-ray diffraction (XRD), and X-ray photoelectron spectroscopy (XPS) were used to characterise the composite. The fibers had a thickness of ~250 nm and uniformly dispersed PAN and SrTiO₃ particles. A PAN/SrTiO₃ composite with a 1:1 mass ratio (20 mg) demonstrated excellent performance, achieving over 90 % degradation at pH 7 and a contaminant concentration of 5 mg/L under ultraviolet (UV) light irradiation during 60 min. The composite was tested for the photodegradation of the major organic pollutant (SMX) in distilled and river water. In river water, the degradation efficiency exceeded 80 % at pH 7 because of the formation of secondary radicals involved in antibiotic degradation. SMX degradation was described using a pseudo-first order kinetic equation using the Langmuir-Hinshelwood model. These results underscore the novelty and significance of the PAN/SrTiO₃ composite and demonstrate its high efficiency and potential for large-scale water purification applications.

1. Introduction

Environmental pollution attributed to pharmaceuticals has become a serious problem because of their active and widespread use [1–3]. Considering that many of them do not naturally decompose, their detection in various water bodies leads to the need for developing new methods for their degradation [1,4–6]. For example, SMX is repeatedly detected in secondary wastewater, which represents the greatest environmental hazard with a maximum concentration of 5 mg/L [7–9]. In addition, even low levels of antibiotics in the environment pose serious threats to human health and environmental safety [10,11]. The World Health Organization (WHO) and Organisation for Economic Co-operation and Development (OECD) projections are disappointing, with the last resort resistance to antibiotics expected to double from

2005 levels by 2035, indicating a significant increase in future antibiotic consumption [12,13].

Conventional water treatment methods have a number of disadvantages; for example, some treatment technologies produce various secondary intermediates, whereas the others are costly, slow, and ineffective with respect to the degradation of organic antibiotics [14,15]. However, oxidation processes, which enable the decomposition of intermediates, have always been considered as universal methods of water purification. Among these methods, the decomposition of organic pollutants using photocatalytic processes is promising because of their solar energy conversion [16], excellent redox capacity [17], low cost [18], low toxicity, and operation under a wide range of environmental conditions [19].

Thus far, various photocatalytic systems such as TiO₂, ZnO, g-C₃N₄,

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and SrTiO₃ have been investigated for water purification using organic pollutants, including antibiotics [20–24]. Among these, SrTiO₃ has attracted considerable interest because of its outstanding redox catalytic activity and environmental safety. It has many properties, which make it a promising candidate for potential applications in various fields such as water separation, wastewater treatment, air purification, and virus inactivation. However, there are a number of limitations, which need to be addressed for the widespread use of composites based on SrTiO₃ for water treatment in the future [25–30]. These limitations are related to low charge separation efficiency, limited conversion of solar radiation attributed to the wide forbidden band of the semiconductor material, and low mobility of photoinduced charge carriers. Recent advances in the synthesis of SrTiO₃-based composites have shown remarkable success in improving the photocatalytic performance of individual materials by creating heterojunctions that not only improve light absorption but also accelerate photoinduced charge separation and transfer. The interaction between modern methods of photocatalyst synthesis and nanotechnology has contributed to the development of new and efficient systems for water decomposition [31,32]. Thus, the electrospinning method represents a versatile, simple, and inexpensive approach to produce composite structures with a high specific surface area to volume ratio and an adaptable composition and morphology [33–38]. In previous studies, a simple and inexpensive method was demonstrated for synthesising SrTiO₃ nanoparticles with excellent photocatalytic activity [39–41]. This activity can be further enhanced by carbon fibers because of their high conductivity, which facilitates the transfer of photoinduced charges.

Composites based on carbon nanofibers and SrTiO₃ were prepared in this study. Electrospinning was used for creating composite structures based on the synthesised SrTiO₃. Composite properties and photocatalytic activity for SMX degradation under UV light were studied systematically. The effects of different SMX concentrations and composite loadings on the photocatalytic decomposition process were demonstrated. The development of such nanostructured photocatalysts is considered an effective approach for extending the photosensitivity range and increasing the separation rate of the photogenerated carriers. The effectiveness of PAN/SrTiO₃ composites in the photocatalytic decomposition of pharmaceutical residues from wastewater was investigated.

2. Experimental

2.1. Materials

Strontium nitrate (Sr(NO₃)₂, purity >98 %), titanium dioxide (TiO₂, particle size: 25 nm, 99.7 %), oxalic acid ((COOH)₂, purity >99.5 %), N,N-dimethylformamide (DMF, >99.8), polyacrylonitrile (PAN with an average molecular weight of 1,300,000), sulfamethoxazole (SMX, C₁₀H₁₁N₃O₃S), sodium hydroxide (NaOH, 98 %), and nitric acid (< 90 %) were purchased from Sigma-Aldrich (Germany).

2.2. Synthesis of SrTiO₃

Sr(NO₃)₂ (2.54 g) and TiO₂ (0.958 g) were mixed in distilled water (100 mL) and ultrasonicated for 30 min [39]. Oxalic acid (5.043 g) was used for precipitation, dissolved, and then gradually added to the premixed solutions. Subsequently, an alkali, ammonium hydroxide, was added to achieve a pH in the range of 6–7. The resulting white precipitate was washed with distilled water five times and dried in a desiccator at 60 °C for 14 h. The synthesis process included chemical precipitation from the TiO₂ and Sr(NO₃)₂ solution and 60 min of calcination in an air atmosphere at 900 °C. The optimum ratio between the TiO₂ and Sr(NO₃)₂ starting reagents was 1:1, enabling us to obtain homogeneous impurity-free SrTiO₃ powder particles by chemical precipitation.

2.3. Synthesis of PAN/SrTiO₃ nanofibers

PAN (0.6 g) was dissolved in DMF (6 mL) and stirred for 30 min at 50 °C until completely dissolved to prepare PAN/SrTiO₃ nanofibers by electrospinning. SrTiO₃ powders with different mass ratios relative to PAN (1:0.5, 1:1, and 1:1.5) were added to the resulting polymer solutions, followed by stirring at room temperature for 30 min. Subsequently, the resulting solution was loaded into a syringe. An electrical voltage of 18 kV was applied to the syringe needle and manifold, and the polymer delivery rate was 1.0 mL/h at 25 °C. An aluminium foil (20 cm in diameter) located 15 cm from the needle served as a collector. The obtained PAN/SrTiO₃ nanofibers were subjected to a carbonisation process conducted in two steps: the first step was heat stabilisation at 270 °C for 60 min, and the second step was calcination at 800 °C in an inert argon atmosphere for 120 min. Synthesised nanocomposites were designated as PS-0.5, PS-1, and PS-1.5. The schematic of the synthesis of the PAN/SrTiO₃ composite is shown in Fig. 1.

2.4. Characterisation

A Zeiss Crossbeam 540 SEM from Germany, operating at voltages between 5 and 20 kV, was utilised to characterise the structural morphology and elemental composition of these materials. The SEM was equipped with a backscattered electron detector coupled with an energy-dispersive X-ray (EDX) spectrometer. An EDX spectrometer (INCA X-Sight, Oxford Instruments) connected to the SEM was used to investigate the size and structure of the composites. Further, XRD was employed to determine the phase compositions of the initial and modified composites. The XRD spectra were acquired using an X-ray diffractometer (Rigaku SmartLab, Japan) equipped with a HyPix-3000 high-energy-resolution 2D HPAD detector. The materials were scanned within a range of 5–70° with a diffraction angle of 2θ at 40 kV and 40 mA. Finally, X-ray photoelectron spectroscopy (XPS) measurements were conducted using a VG-Microtech Multilab 3000 device equipped with a 9 channeltrons hemispherical electron analyser and X-ray radiation source employing Mg and Al anodes.

2.5. Photocatalytic test

Photocatalytic experiments were conducted using a Shleewen photochemical reactor (Shanghai Leewen Scientific Instrument Co., Ltd., China). The decomposition of the different concentrations of SMX (5, 10, and 20 mg/L) under UV light was used for evaluating the photocatalytic activities of the synthesised materials. A 10 W mercury lamp (The illumination intensity is adjusted to 12 W/m²) (Zhuozhou Xupurui, Ltd.) was used as the light source. In brief, 20 mg of the photocatalyst was added to 50 mL of the SMX solution and stirred in the dark for 30 min to observe the equilibrium and maximum adsorption efficiency. A total of 1.3 mL of the mixture was sampled at 10 min intervals during irradiation and then filtered through a 0.22 μm (13 mm diameter). The pH of the photocatalytic reaction was 7. NaOH-H₂NO₃ buffer and deionised water were used for pH adjustment. The prepared mixture was added to the contaminant solution for achieving pH values of 2, 4, 7, 8, and 10. Photocatalytic decomposition was analysed using different PAN/SrTiO₃ parameters (1/0.5, 1/1, and 1/1.5), and the pH was varied between 2, 4, 6, 8, and 10 at a concentration of 5 mg/L. The SMX solutions subjected to photocatalytic decomposition were analysed using an I5 UV–Vis spectrophotometer (Hanon Advanced Technology Group Co., Ltd.). The options for this spectrophotometer include 24-bit high-speed analogue-to-digital conversion and increased instrument sensitivity. The bandwidths were automatically adjusted to 0.5, 1.0, 2.0, 4.0, and 5.0. For the analysis, 1 mL of the filtered mixture was added to a quartz cuvette and diluted with 2 mL of distilled water. The detection wavelength was 265 nm. Tap water collected in Almaty City (Kazakhstan) was not subjected to filtration and stored at room temperature for 3 days. River water, also collected from the Yesentai River

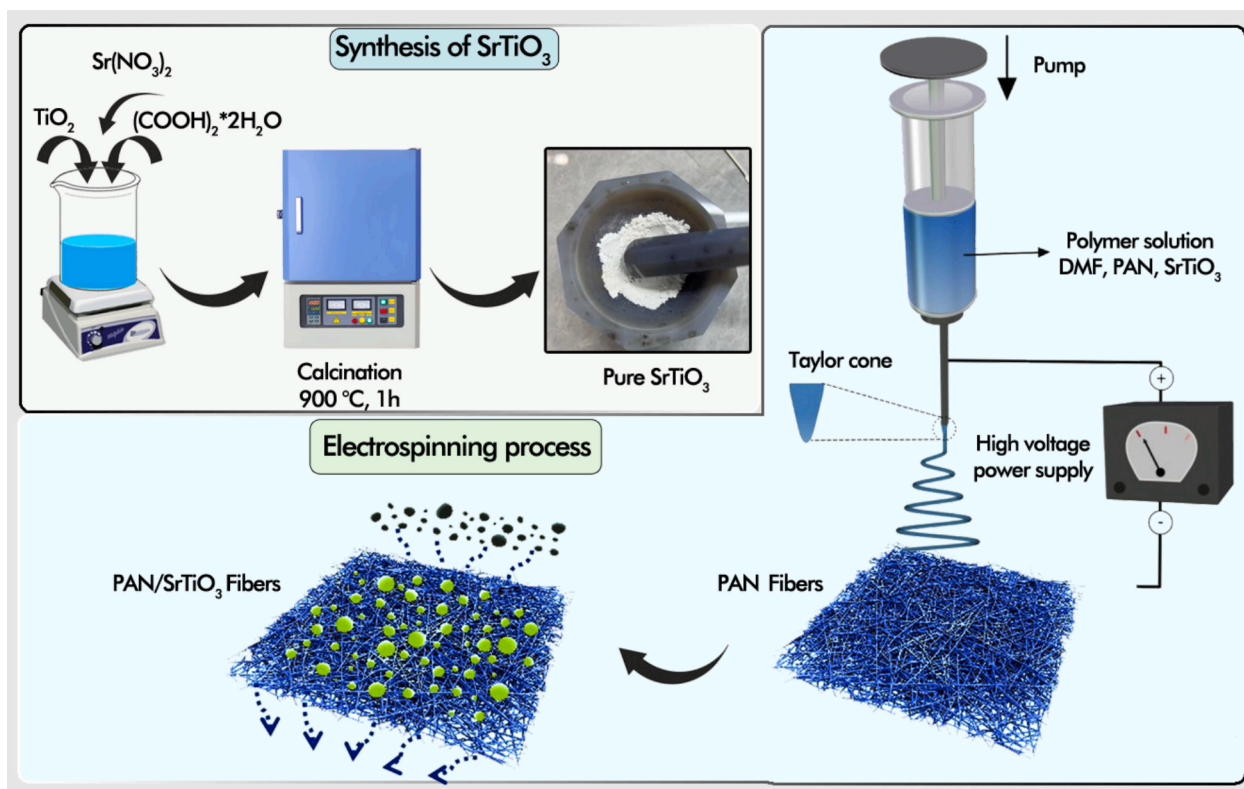


Fig. 1. Schematic of the preparation for PAN/ SrTiO_3 nanofibers.

in Almaty, was filtered through 90 mm pores to remove large impurities before being used in the experiment.

3. Results and discussion

3.1. Characterisation

Fig. 2A and B shows the analysis of the surface morphology of the obtained samples using SEM. The successful growth of typical agglomerated nanoparticles whose sizes are in the range of 50–150 nm and

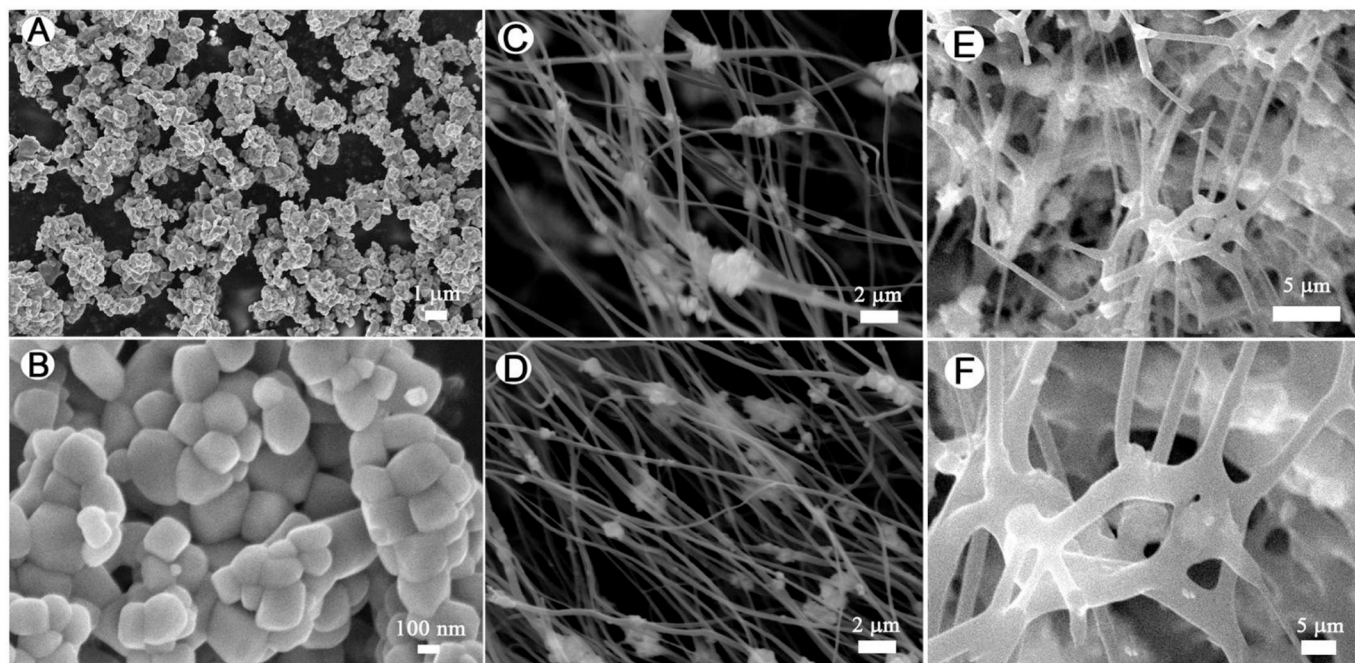


Fig. 2. SEM images obtained pristine SrTiO_3 nanocubes (A, B), PAN/ SrTiO_3 nanofibers before (C, D) and after thermal treatments (E, F).

directly depend on the calcination temperature are observed for the obtained SrTiO_3 [42]. Although the amount of impurities in the form of SrCO_3 is still high, the study reported in [43] indicate that calcination in the range of 750–900 °C forms smaller SrTiO_3 particles. Increasing the calcination temperature to 900–1100 °C favours a faster decomposition of the carbonate and the formation of titanate [44]. However, despite the increase in purity upon calcination in the range of 1000–1100 °C, the particle size of SrTiO_3 increases to the micrometre scale. This increase in size can adversely affect the efficiency of photocatalytic reactions because more effort is required to transport photogenerated electrons and holes to the surface, which is accompanied by an increased probability of recombination (charge fusion) [20]. Based on these data, 900 °C was determined as the optimum calcination temperature, and subsequent treatment in 1 M nitric acid solution favoured the effective degradation of residual SrCO_3 . Further, EDX mapping confirmed the presence of Ti, O, and Sr without any other impurities in the composition (Supplementary, Fig. S1). Fig. 2C–F shows SEM images of the obtained PAN/ SrTiO_3 composites. Before heat treatment (Fig. 2C and D), the samples are chaotically formed uniform nanofibers with diameters between 250 and 900 nm, on which the agglomerates of SrTiO_3 particles are observed, as confirmed by the EDX spectrum (Supplementary, Fig. S2). A marked decrease in nanofibers diameter with breaks and abundant defects was observed when the nanofibers were heat treated at 800 °C, which can improve the photocatalytic reactions attributed to additional active centres (Fig. 2E and F). Further, calcification resulted in large, interconnected openings and a fully formed three-dimensional fibrous network. Previously, similar studies have reported a decrease in nanofibers size after the annealing process [45,46]. This may be because of the partial degradation of the polymer component and/or carbonisation during heat treatment.

The X-ray spectra of the synthesised SrTiO_3 and PAN/ SrTiO_3 samples were studied using X-ray phase analysis (XRD) for determining their crystal structures (Fig. 3). The results of the analyses of the SrTiO_3 powder indicated that the obtained sample had a cubic structure. The value of the unit cell period was $a = 3.905 \text{ \AA}$, which agreed with the literature data [47,48]. The characteristic peaks of the SrTiO_3 samples appeared at 2 θ , 32.40, 40.50, 46.50, 58.50, and 68.50, and they are assigned to (110), (111), (200), (211), and (220) planes of cubic symmetry of SrTiO_3 , agreeing well with the standard map for SrTiO_3 (JCPDS Card #35-0734) and confirming the confidence in the material's crystallinity. The PAN/ SrTiO_3 XRD patterns indicate that the diffraction peaks of the sample are in good agreement with those for the synthesised SrTiO_3 , with no shift or change in the peak shape, which indicates that the combination with PAN does not affect the crystal structure. A similar

pattern has been observed for other SrTiO_3 and polymer-based composite nanofibers [49–51].

The analysis of the TEM images of the sample (Fig. 4A and B) indicates that the agglomerates consist of small crystals whose interplanar distance is 0.38 nm, which is related to the (110) crystallographic planes of the cubic perovskite structure (Supplementary Fig. S3). These results closely correlate with those obtained in several other studies [52,53] and indicate that particle aggregation is irreversible and occurs in a highly oriented manner, thereby leading to the elimination of the interface between neighbouring crystals. XPS was used to investigate the chemical composition and surface structure of the SrTiO_3 photocatalyst obtained by chemical deposition. Fig. 4C shows the XPS spectrum of pure SrTiO_3 , which contains no impurities except for a small amount of carbon. The C 1s peak was caused by surface contamination during the test. Fig. 4E shows the XPS spectrum for the photoelectron emission from the Ti 2p nucleus, which is consistent with that reported in previous studies [54,55]. The two peaks at energies of 457.4 and 463.2 eV correspond to the spin-orbit coupling of Ti 2p_{3/2} and Ti 2p_{1/2} to Ti⁴⁺ ions, whereas the peak at 462.4 eV indicates the presence of Ti³⁺ ions in the sample [56]. The O 1s spectrum in Fig. 4D was decomposed into two Gaussian peaks. The main peak at 528.4 eV is attributed to O²⁻ ions in the crystal lattice (O_L), whereas the peak at 530.0 eV corresponds to the adsorbed oxygen species associated with oxygen vacancies (O_V). The O_L to O_V ratio was 0.19, consistent with the results of the previous studies. An appropriate amount of O_V positively affects the photocatalytic properties by preventing the recombination of photogenerated charge carriers [57]. Fig. 4F shows two peaks at 132.6 and 134.3 eV corresponding to the Sr 4d level nuclei [55]. Binding energies obtained for SrTiO_3 synthesised by chemical precipitation followed by calcination at 900 °C were in good agreement with those of pure SrTiO_3 obtained via other methods [44,54,55]. Thus, the analysis of XRD and XPS results further confirmed the successful synthesis of cubic SrTiO_3 .

3.2. Photocatalytic performance

Photocatalytic performances of the obtained composites were studied in relation to the decomposition of SMX under UV irradiation. The experiments with different initial SMX concentrations (5, 10, and 20 mg/L) showed that the degradation profile decreased with increasing SMX concentration (Fig. 5A–F). The PS-1 composite exhibited the highest photocatalytic activities of 90.23, 82.86, and 74.00 % at concentrations of 5 (Fig. 5A), 10 (Fig. 5C), and 20 mg/L (Fig. 5E), respectively. This phenomenon can be attributed to two factors: (1) The time of complete decomposition increases with increasing antibiotic concentration and the photocatalytic degradation process slows down [58]. (2) The transmission of light through the solution decreases with an increase in the concentration of SMX, which reduces the radiation energy absorbed by the photocatalyst, consequently decreasing the efficiency of the photocatalytic process [59]. Composites PS-0.5 and PS-1.5 showed less degradation of antibiotics but followed the same trend in terms of composite efficacy. The increase in the SrTiO_3 loading in the case of the PS-1.5 composite photocatalytic efficiency was lower than that in PS-1. This is probably because excess SrTiO_3 particles have a strong tendency to agglomerate, which limits their actual contact with carbon nanofibers. Similar photocatalytic characteristics, where the effect of catalyst loading is relative to the polymer, have been reported in other studies [60,61]. For example, in the case of the PAN/ TiO_2 /PANI composite, increasing the TiO_2 content by factors of two and four increased the photoactivity towards Congo Red degradation from 70 % to 77 % and 84 %, respectively, when irradiated with visible light for 5 h [60]. Thus, determining the optimal photocatalyst concentration can help improve the overall photocatalytic efficiency of composites. The rate kinetics of the SMX photocatalytic degradation were determined using the Langmuir–Hinshelwood pseudo-first-order rate kinetics model using Eq. (1):

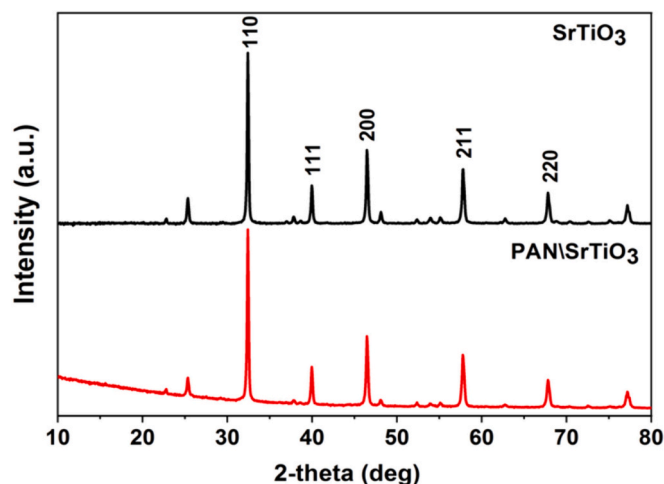


Fig. 3. X-ray pattern of the synthesised SrTiO_3 powder and PAN/ SrTiO_3 nanofibers (JCPDS Card #35-0734).

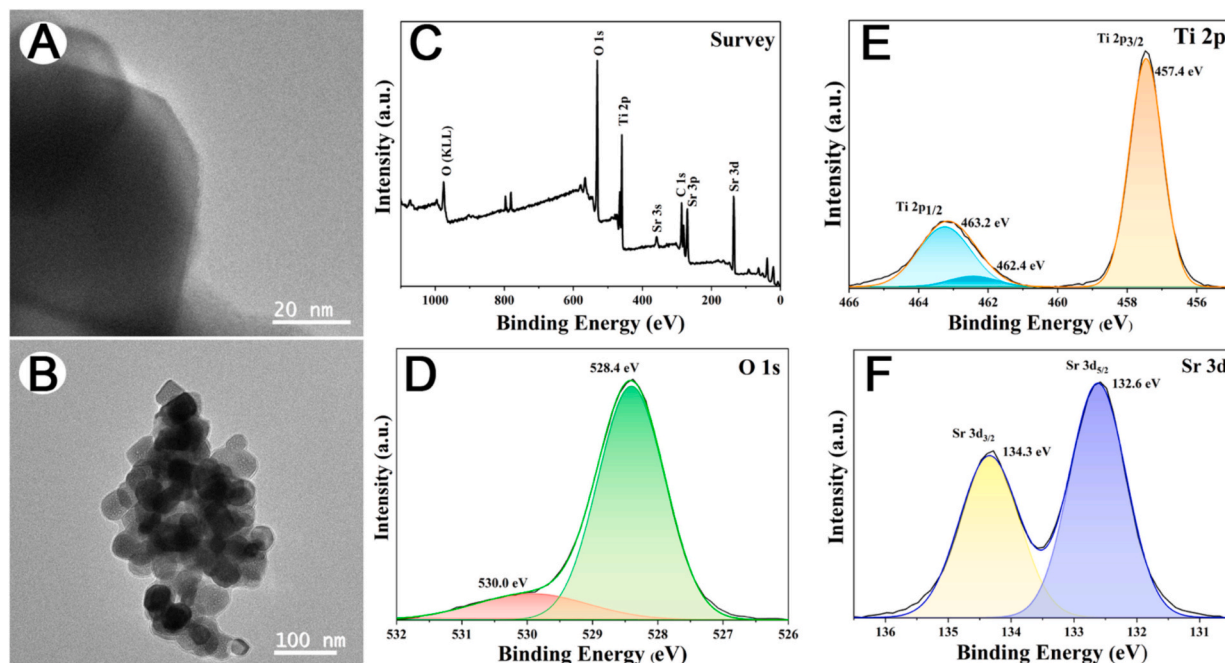


Fig. 4. TEM images (A, B) and XPS spectra (C–F) of the obtained SrTiO₃ nanocubes.

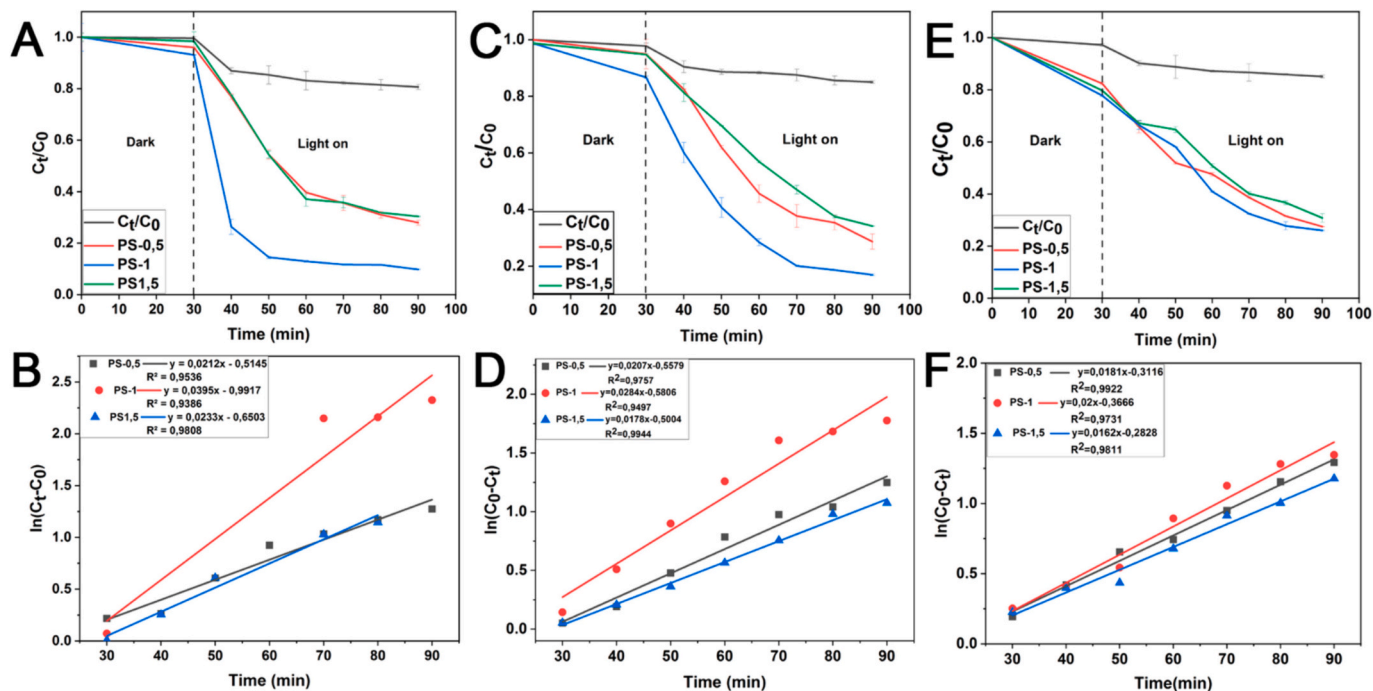


Fig. 5. Photocatalytic degradation activity of PS-0.5, PS-1, and PS-1.5 at SMX concentrations of 5 (A); 10 (C); and 20 mg/L (E). Plots of $\ln(C_0/C_t)$ versus times at SMX concentrations of 5 (B); 10 (D); and 20 mg/L (F).

$$-\ln\left(\frac{C_t}{C_0}\right) = k_p t, \quad (1)$$

where C_0 and C_t (mg/L) represent the initial concentrations at time t and k_p represents the rate constant of the reaction. The reaction rate constants were calculated for all three composites as a function of the initial SMX concentration (Supplementary Table 1, Fig. S4). At a concentration of 5 mg/L, the reaction rate constants (Fig. 5B) for the PS-0.5, PS-1 and PS-1.5 composites were 0.0212, 0.0395, and 0.0233 min⁻¹ respectively. For concentrations of 10 (Fig. 5D) and 20 mg/L (Fig. 5F), the values of

the reaction constants for samples PS-0.5, PS-1, and PS-1.5, were (0.0207, 0.0284, and 0.0178 min⁻¹) and (0.0181, 0.02, and 0.0162 min⁻¹) respectively. However, concentrations above 5 mg/L were not observed under near-realistic conditions, because the presence of SMX can range from 10 to 1500 ng/L in wastewater, 0.2–1100 ng/L in groundwater, and from ~100 pg/L to several ng/L in water intended for human consumption, despite being one of the most common antimicrobial contaminants [60,62–65].

Further studies were conducted to investigate the effect of solution pH on the photocatalytic decomposition efficiency of SMX using the PS-

1 composite. Fig. 6A shows the results of the SMX degradation experiments at pH values of 2, 4, 6, 8, and 10. The results showed that an acidic environment favoured the efficient decomposition of SMX such that at pH 2, the decomposition efficiency reached 100 % in 40 min. There was a noticeable decrease in efficiency with an increase in the pH of the solution; at pH 4, it was 97.22 % (50 min), and at pH 6, 90.2 %. At a solution pH of 10, the degradation of SMX decreased significantly to 83.20 %. Therefore, the efficiency of the photocatalytic decomposition of SMX using PS-1 was better in acidic environments than in neutral and slightly alkaline conditions. This suggests that the pH of the SMX solution is closely related to the rate of photocatalytic degradation. Changes in pH conditions affect the decomposition of the SMX structure and protonation at $\text{pH} < \text{pK}_{\alpha 1}$ inhibits unpaired electron transfer, whereas deprotonation at $\text{pH} > \text{pK}_{\alpha 2}$ enhances radical oxidative activity [66]. Simultaneously, the surface properties and charge of the composite change with increasing pH, which leads to a significant decrease in the photocatalytic degradation rate. Presumably, at pH values below 6, the composite has a positive charge because of which it can electrostatically adsorb SMX, followed by direct photocatalytic decomposition on the composite surface. The adsorption performance of the prepared composite PS-1 for SMX was investigated by adsorption experiments, which were performed exactly as that for photocatalytic decomposition without including UV light (Fig. 6B). The obtained data indicate that the adsorption capacity of the composite towards SMX was low at 5, 18, and 35 % for river water, tap water, and distilled water, respectively. Studies conducted with different masses of the PS-1 composite (10, 20, and 30 mg) showed that the highest photocatalytic degradation efficiency of SMX (91.97 %) was obtained with 30 mg composite loading (Fig. 6C). However, at 20 mg loading, the efficiency is comparable (90.23 %); this small difference could be attributed to there being enough active centres and electron holes created at this composite density for SMX mineralisation (5 mg/L). This implies that the catalytic effect with the addition of 20 mg was sufficient, and there was no need to further increase the mass of the composite.

Further studies were conducted to investigate the dependence of SMX degradation efficiency on the type of aqueous matrix, which has a significant effect on the photodegradation process [67,68]. Water

samples were collected from Yesentai River in Almaty, Kazakhstan. Fig. 6D shows the degradation efficiencies of SMX with PS-1 in different aqueous media; the efficiencies were 80.81 and 93.07 % for river water and tap water, respectively. This is because of the effect of natural organic substances, such as humic, tartaric, oxalic, and ethylenediaminetetraacetic acids. However, the overall decomposition efficiency in river water (80.81 %) indicated that the obtained photocatalyst was promising for use in real water environments. Notably, the efficiency was lower for distilled water (90.23 %) than for tap water (93.07 %) probably because of the photocatalytic degradation mechanism. The degradation mechanism may be different depending on the type of water; for example, according to a previous study [69], $\cdot\text{OH}$ is the main radical involved in the degradation of SMX. For rivers and seawater, the main participants in the photocatalytic decomposition mechanism are halogen radicals formed because of the direct oxidation of halide ions h^+ . Although less reactive than $\cdot\text{OH}$, they exhibit higher selectivity towards compounds with electron-rich functional groups [70]. The resulting composite could remove $>80\%$ of the organic pollutants, making it versatile regardless of the radicals involved in the decomposition process. Considering that photocatalysts have been proposed for wastewater treatment after biological treatment, the proposed composite shows great promise for real applications.

Thus, studies on the photocatalytic decomposition of SMX molecules indicated the effectiveness of the composites in removing organic pollutants. The obtained results correlate with those of previously published studies and confirm the mechanism of SMX photodegradation, which involves the reaction of organic pollutant molecules with active O and/or OH particles formed because of photoinduction. Carbon fibers, which are known for their high electrical conductivity, contribute to the efficient separation of the photoinduced electrons and holes formed on the surface of SrTiO_3 . Studies conducted on the decomposition of SMX in river water showed that, for this composite, the decomposition efficiency was at the same high level ($>80\%$) as that of distilled water.

Sample PS-1 successfully passed the stability test by surviving five cycles. As shown in Fig. 7, the photocatalyst maintained nearly constant activity during the photodegradation of SMX solution with a concentration of 5 ppm for all five cycles. However, the degradation efficiency

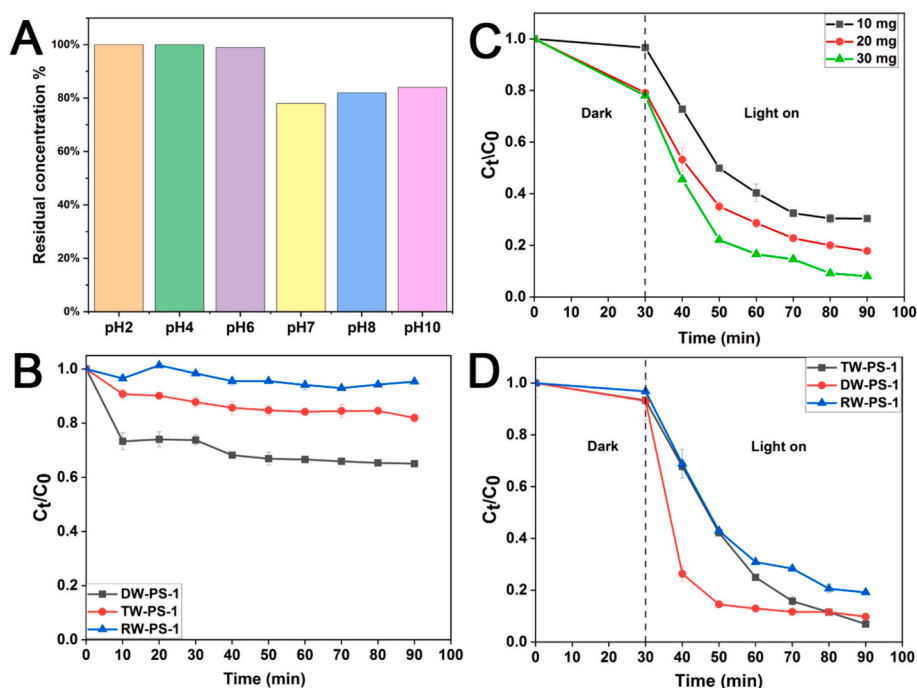


Fig. 6. Photocatalytic degradation of SMX using nanocomposite PS-1: Effect of pH value (A); adsorption performance at different aqueous media (B); effect of catalyst dose (C); and at different aqueous media (tap water (TW), distilled water (DW), river water (RW)) (D).

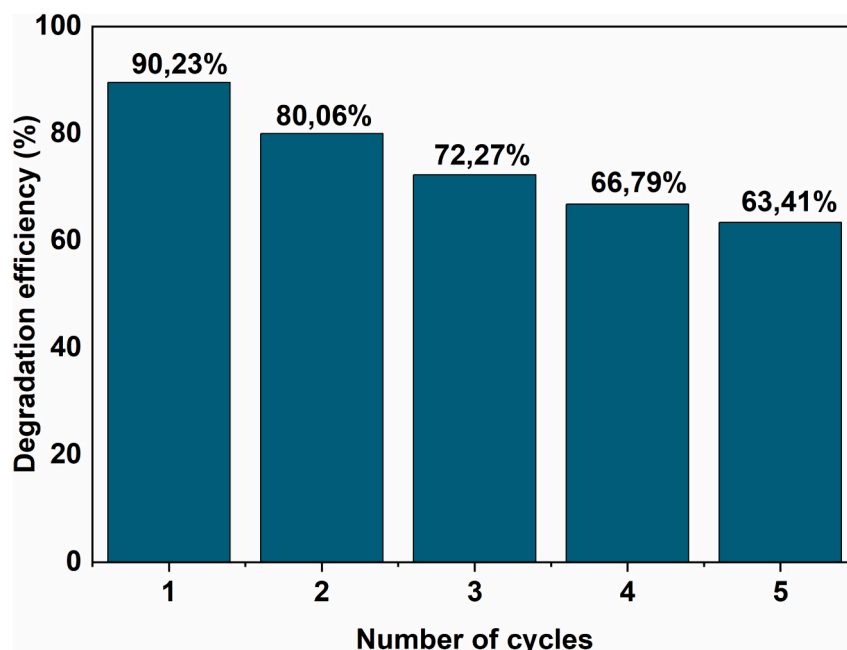


Fig. 7. Cycle stability experiment of PS-1 photocatalyst.

decreased from 90.23 % to 63.41 %, which is probably due to the accumulation of adsorbed SMX intermediates on the surface of the photocatalyst during repeated use. This test confirms that the PS-1 sample is highly robust and maintains its efficiency in SMX degradation over several cycles.

4. Conclusion

The PAN/SrTiO₃ composite was synthesised successfully by high-temperature sintering and electrospinning and applied as an efficient photocatalyst for the degradation of SMX from aqueous solutions. The PS-1 composite (20 mg) exhibited the best performance with a degradation efficiency of >90 % at pH 7 and a contaminant concentration of 5 mg/L. The effects of different parameters on the photocatalytic decomposition of SMX are demonstrated. The resulting composite was tested for the photodegradation of a major organic pollutant (SMX) from distilled and river water matrices. In river water, the degradation efficiency exceeded 80 % at pH 7 because of the possible formation of secondary radicals that could be involved in the degradation of the antibiotic. The obtained results provide a basis for the further investigation of organic pollutant degradation in wider water quality samples to better understand the degradation mechanisms and select the necessary structural properties of the composite for its optimal performance under real wastewater conditions. Thus, the presented results demonstrate that a combination of simple methods and outstanding degradation efficiencies can facilitate the potential application of PAN/SrTiO₃ composites on a larger scale. In addition, testing the degradation of additional emerging impurities of various chemical natures at ambient concentrations can help determine the potential versatility of the proposed water treatment composite.

CRedit authorship contribution statement

Aigerim Serik: Writing – original draft. **Zhengisbek Kuspanov:** Methodology, Investigation, Conceptualization. **Madina Bissenova:** Methodology, Investigation, Conceptualization. **Nurlan Idrissov:** Methodology, Investigation, Conceptualization. **Mukhtar Yeleuov:** Resources, Formal analysis. **Arman Umirzakov:** Resources, Formal analysis. **Chingis Daulbayev:** Writing – review & editing, Project

administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jwpe.2024.106052>.

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