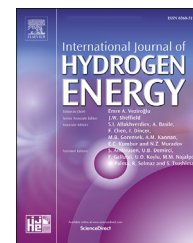


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Review Article

Multifunctional strontium titanate perovskite-based composite photocatalysts for energy conversion and other applications



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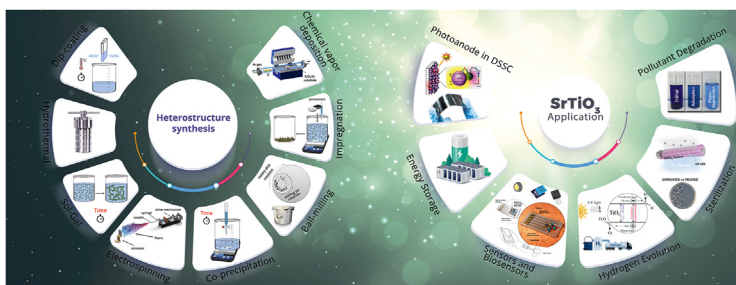
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HIGHLIGHTS

- The main strategies to overcome the limitations of SrTiO₃ based photocatalysts in various applications are presented.
- The synthesis methods of composites based on SrTiO₃ for photocatalytic applications were discussed.
- The potential applications of SrTiO₃-based composites in solving environmental and energy-related problems are explored.

GRAPHICAL ABSTRACT



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ABSTRACT

The detrimental impact of human activity on the global ecological situation has resulted in the active exploration and development of alternative energy sources. Efficient solar energy utilization can significantly contribute to resolving the current energy crisis, because approximately 1.36 kW m^{-2} of solar radiation reaches the Earth's surface, and this can be used to satisfy the global energy requirements. Among various prevalent sunlight conversion technologies, photocatalytic materials are potentially useful for hydrogen production and other relevant applications. Existing technologies for the production and use of photocatalysts do not sufficiently address the target characteristics owing to the low solar conversion efficiency and service life in addition to high costs. However, recent advances in SrTiO₃-based heterostructures indicate that photocatalysts can potentially compete with modern solar energy technologies in terms of their practical application. In

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H₂ evolution
N₂ fixation
Pollutants degradation

this review, we systematically consider the advancement in the production and application of SrTiO₃-based photocatalysts in various fields. The methods for obtaining complex heterostructures with different classes of nanomaterials are comprehensively discussed. The aim of this review is to highlight the advantages and limitations of using SrTiO₃-based photocatalytic systems. Finally, the future prospects of using SrTiO₃-based photocatalysts are considered from the perspective of their practical applications.

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Abbreviations

ALD	atomic layer deposition
BRO	bromhexine
CB	conduction band
CIP	ciprofloxacin
CNT	carbon nanotube
CTC•HCl	aureomycin hydrochloride
D _{max} -D _{rem}	electric displacement difference
DPH	diphenhydramine
Eb	breakdown strength
FAME	fatty acid methyl ester
J _{sc}	short circuit current density

MB	methylene blue
MO	methyl orange
NHE	hydrogen electrode
PBS	phosphate-buffered saline
RhB	rhodamine B
SILAR	sequential ion layer adsorption reaction
SMX	carbamazepine
TBT	tetra- <i>n</i> -butyl orthotitanate
TC	tetracycline
TEOA	triethanolamine
U _e	energy storage density
VB	valence band
V _{OC}	circuit voltage

Introduction

Studies aimed at identifying sustainable and environmentally friendly energy sources are of considerable interest owing to the negative impact of fossil fuels on the environment [1–5]. Therefore, several programs and strategies have been adopted to develop and implement technologies for the use of alternative energy sources. The 2019–2025 Global Strategy for Sustainable Energy is one such program adopted by the United Nations and the Green Deal project (with an annual investment of €260 billion), which aims to reduce greenhouse gas emissions in the European Union by up to 32% and shift to a carbon-neutral society by 2030 [6]. Such strategic development programs are also being adopted in the Central Asian region. For example, Kazakhstan has adopted a concept for the development of the fuel and energy sector until 2030, with the aim of developing and expanding the role of alternative and renewable energy sources and implementing a decarbonisation policy.

Efficient solar energy utilization can significantly contribute to the successful implementation of these programs and development strategies. Although technologies are available for the efficient conversion of sunlight into energy, photocatalysts that can produce pure hydrogen and purify water and air from various pollutants by converting light have attracted considerable interest. The discovery of photocatalytic decomposition of water in 1972 [7] marked the beginning of numerous studies, and this field has witnessed significant progress thus far. Numerous types of photocatalysts, such as TiO_2 , SrTiO_3 , NaTaO_3 , ZnO , Co_3O_4 , and Fe_2O_3 , have been discovered and investigated [8–12]. The quantum efficiencies of solar light conversion for all photocatalysts are typically low and depend on the sensitivity of the photocatalytic system to the visible spectrum. For example, theoretical calculations indicate that solar energy can be converted into hydrogen by at efficiencies up to 15% if a solar spectrum below 600 nm is used [13,14]. The actual quantum efficiency for the photocatalytic decomposition of water is only 1% [15].

The quantum efficiency of a photocatalyst for converting light into electrochemical energy depends on the following parameters: 1) the band gap, which should be comparable to the photon energy in the visible region of the spectrum (2.0–2.4 eV); 2) a low number of recombination of photoinduced electron–hole pairs, which have high mobility; 3) resistance to the aquatic environment, temperature, acid–base solutions, and sunlight; 4) free diffusion of water molecules. A possible solution to improve the solar conversion efficiency is the creation of hybrid composite structures, which can reduce the band gap of the photocatalyst and improve light absorption. In this regard, strontium titanate (SrTiO_3) is suitable for creating hybrid composite photocatalyst systems owing to several advantages. First, this semiconductor material is a well-researched photocatalyst with a band gap of 3.2 eV [16]; second, numerous studies have indicated the formation of SrTiO_3 -based composite structures, whereby the photocatalytic decomposition of water is improved by 69% compared with the process using pure SrTiO_3 powder [17–20]. In addition, SrTiO_3 has been

successfully used in the manufacture of panels with a total area of 100 m² for hydrogen production [21].

Over the past decade, numerous research articles containing the keyword SrTiO_3 have been published. The growing interest in SrTiO_3 is evidenced by fundamental research [22–26] devoted to theoretical and practical aspects, which allow us to consider the prospects and problems of using this perovskite in various fields. These studies indicate that the type of co-catalyst and the method of synthesising the heterostructure significantly affect the SrTiO_3 structure; consequently, the properties of the SrTiO_3 -based composite structures are modified. From this perspective, we believe that the properties of SrTiO_3 -based heterostructures must be comprehensively examined to elucidate the relationship between the synthesis parameters of SrTiO_3 -based composites and the characteristics of their applications. In this review, methods for obtaining SrTiO_3 -based composites and recent advances in their practical application are considered. We analyse the influence of the method of obtaining SrTiO_3 -based composites on the mechanism and efficiency of their practical application in various fields. Finally, the problems and future prospects for the use of SrTiO_3 and its composites in various fields are discussed.

Methods for obtaining SrTiO_3 and SrTiO_3 -based composites

The use of pure SrTiO_3 is not of particular interest owing to several factors, such as extremely low efficiency, attributed to the rapid recombination of photogenerated electrons and holes, and a wide bandgap, which reduces the solar energy absorption spectrum. Creating heterojunctions based on SrTiO_3 and various other materials addresses their limitations and significantly contributes to the creation of new types of photocatalysts. Conventional methods for synthesising SrTiO_3 include hydro/solvothermal [27–29], solid-phase [30], sol–gel [31], co-precipitation [32], and hybrid methods. SrTiO_3 nanoparticles with various shapes and sizes can be obtained through the application of various methods and their combinations. In particular, the solid-phase method results in chemically pure cube-like SrTiO_3 particles with an average size of 75 nm [33]. The hybrid sol–gel–solid phase method is environmentally friendly and enables the synthesis of SrTiO_3 nanoparticles with a smaller size (34 nm) [34]. The advantages of hydro/solvothermal methods include the ability to control the morphology of the SrTiO_3 nanoparticles by adjusting the synthesis conditions. Graphic illustrations of different approaches for obtaining SrTiO_3 -based composites are shown in Fig. 1.

When heterostructures are created by methods that affect the photocatalytic properties, the main problems are: 1) insufficiently close contact between two or more phases for free exchange of charge carriers; 2) inability to control the size, morphology, and crystallinity to obtain pure, homogeneous heterostructures of the required shape; and 3) difficulty in creating unique surfaces or mesoporous structures with a high specific area to provide numerous reaction centres. In this section, we discuss recent advances in the synthesis of SrTiO_3 -based photocatalysts, because the production of

highly efficient heterostructured photocatalysts at low cost and without environmental harm is an urgent challenge.

Hydrothermal method

The conventional hydrothermal method can be used to efficiently synthesise both crystalline SrTiO_3 and related heterostructured composite materials. The primary advantage of this method is the improvement in the crystallinity, crystallite size, and morphology at moderate temperatures. The other advantages of this method include simplicity, environmental friendliness, and the ability to control the surface chemical composition by controlling the type of solvent, sol composition, holding time, pressure, and reaction temperature. Particularly, multilayer composites with desired shapes can be created. Thus, a simple hydrothermal method can yield hollow multi-shell homogeneous structures of SrTiO_3 doped with La and Rh (STOLa/Rh) [35] and $\text{SrTiO}_3\text{--TiO}_2$ [36]. In addition to multi-shell structures, nanocomposites (CdSe/SrTiO_3) with quasi-spherical structures and rough surfaces can be obtained through the hydrothermal method [37]. Simultaneously, the structure of such a heterojunction, which is formed by modifying quantum dots (CdSe) on the surface of SrTiO_3 nanoparticles, improves its photocatalytic characteristics. Another promising hybrid photocatalytic system is the ZnO/SrTiO_3 nanocomposite, which is obtained through a low-cost hydrothermal method and consists of ZnO nanosheets modified with SrTiO_3 nanospherical particles [38]. For this system, analysing the chemical composition using X-ray photoelectron spectroscopy and maps of the spatial distribution of atoms indicate that pure composites are produced with ZnO--SrTiO_3 atomic interfacial contact; thus, successful hydrothermal synthesis is confirmed. Hybridisation and creation of a heterogeneous ZnO semiconductor with a wide-band SrTiO_3 photocatalyst reduces the recombination of photoexcited excitons, thereby increasing the photocatalytic activity.

Obtaining sufficient close contact and a strong chemical bond between the components is crucial for the successful synthesis of highly efficient heterojunction photocatalysts. For example, the composite photocatalyst rGO@SrTiO_3 obtained through the hydrothermal method demonstrates the formation of a sufficiently strong chemical bond, which is associated with a possible improvement in the photocatalytic properties of the rGO@SrTiO_3 nanocomposite, in contrast to the separate use of pure SrTiO_3 or rGO [39]. In addition, a heterostructure composite consisting of Ag-doped STO/g-CN was synthesised for the efficient photocatalytic production of hydrogen and decomposition of the pesticide dicofol; the hydrothermal reaction was found to contribute to the close contact between the g-CN nanosheets and STO and Ag nanoparticles, thus increasing the efficiency for photocatalytic applications [40].

Fast recombination of electron–hole pairs and a relatively narrow absorption region of visible light are regarded as the predominant problems that reduce the photocatalytic performance. The construction of heterojunctions from two suitable semiconductors, that is, in the form of a Z-scheme, is of considerable interest because such a structure suppresses the recombination of photoinduced charge carriers. For example, the formation of such Z-scheme heterojunctions with zero-dimensional carbon nanomaterials through a simple hydrothermal method can consequently expand the light absorption range [41].

Solvothermal method

In contrast to the hydrothermal synthesis method, wherein water is used, the solvothermal process involves heating the initial solutions in organic or inorganic compounds in special Teflon-coated autoclaves at temperatures exceeding the boiling point of the solvent and under pressures exceeding 0.1 MPa. The desired crystal structure, morphology, and

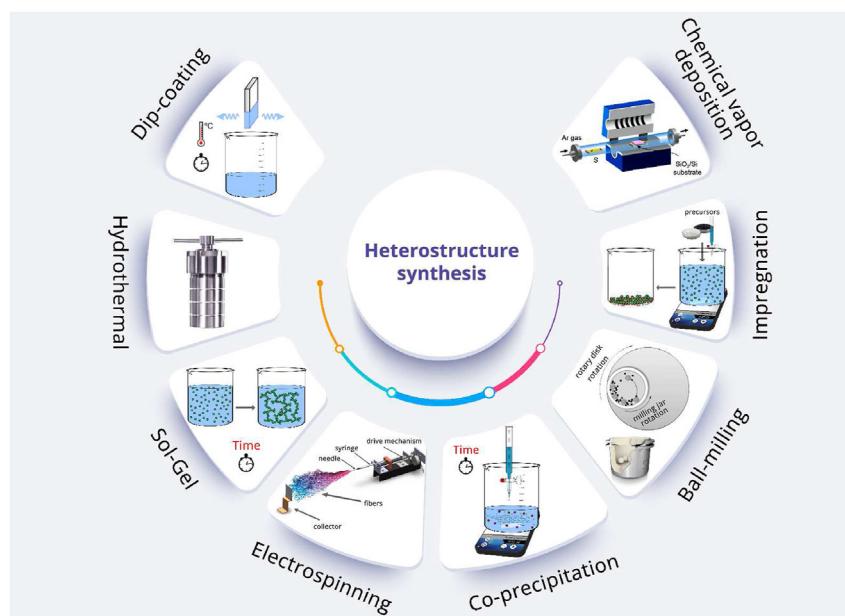


Fig. 1 – Different methods for obtaining SrTiO_3 -based heterostructures.

particle size can be achieved by adjusting the reaction conditions. The solvothermal method also facilitates sufficiently close contact between the photocatalyst heterojunctions of SrTiO₃-based nanocomposites. For example, the solvothermal method can promote close contact between La-WO₃ and SrTiO₃ in a nanostructured heterojunction composite, La-WO₃@SrTiO₃ [42]. In addition, under certain reaction conditions, ultrathin nanovilli with an average diameter of 50 nm grow on the surface of the La-WO₃ particles in the samples, contributing to the high adsorption of reactive substances and efficient absorption of visible light. In another study [43], BiOI-decorated SrTiO₃ nanofibres were obtained via rapid solvothermal treatment using microwave radiation for methyl orange (MO) photodegradation under visible-light irradiation. The solvothermal method resulted in the formation of a p–n junction at the interface between SrTiO₃ and BiOI, which improved the electron–hole transfer. Simultaneously, the resulting nanocomposite has a spike-like structure with mesopores (size = 31 nm) providing a large contact area, thereby increasing the photocatalytic efficiency during dye decomposition, with a degradation rate of 0.015 min^{−1}. In addition, the solvothermal method has been used to synthesise a porous graphene/SrTiO₃ nanocomposite with a morphology similar to that of a washcloth, wherein SrTiO₃ nanospheres are wrapped in sheets of porous graphene. Such a structure increases the contact area between porous graphene and SrTiO₃, thus improving the charge carrier transport [44].

Sol–gel method

The advantages of the sol–gel method over various other methods for synthesising nanocomposite heterostructured SrTiO₃-based photocatalysts include the high purity of the synthesised homogeneous nanopowders and the possibility of controlling their chemical properties. These advantages are achieved by mixing liquid starting reagents at the molecular level during synthesis. For example, a high-purity mesoporous heterostructured TiO₂@SrTiO₃ nanocomposite was obtained through the sol–gel method by mixing pre-dispersed tetra-*n*-butyl orthotitanate (TBT) and Sr(NO₃)₂ precursors in 20 mL of ethanol and thoroughly stirring for 30 min until a transparent sol and gel were formed. Using the sol–gel method, a relatively small size (approximately 24.49 nm) of the TiO₂@SrTiO₃ nanocomposite with a considerably high porosity of 126.8 m² g^{−1} could be obtained [45]. Owing to the complete control of the reaction conditions in the sol–gel method, a highly efficient CoAlMnO₄@SrTiO₃ heterojunction with optimal morphology and particle size could be synthesised; this heterojunction was subsequently used for producing hydrogen by the photocatalytic decomposition of water under both ultraviolet (UV) and visible radiation [46]. Furthermore, optimised synthesis conditions facilitated the configuration of a type-I heterojunction with a core–shell structure, wherein CoAlMnO₄ nanoparticles (10 nm) and SrTiO₃ (20 nm) served as the core and shell, respectively.

The sol–gel technology is distinguished by its simplicity; moreover, high temperatures and pressures are not required during synthesis. For example, a porous heterojunction SrTiO₃/SrSO₄ nanocomposite was created using a one-pot

sol–gel method at a moderate temperature, followed by annealing and photodeposition of Pt nanoparticles [47]. The resulting data indicate the high crystallinity and porosity of the SrTiO₃@SrSO₄ heterojunction with increased photocatalytic activity. The characteristics of multicomponent nanocomposite photocatalysts are significantly superior to those of photocatalysts with individual components; for example, ternary systems improve the photogeneration of electron–hole pairs and enhance the light-absorbing ability of the photocatalyst. The use of carbon nanotubes (CNTs), which have excellent properties such as high conductivity and large specific surface area in ternary systems, makes the photocatalyst promising for photocatalytic applications. Ternary plasmon nanocomposites Ag@SrTiO₃@CNT were successfully synthesised using the sol–gel method for the efficient photocatalytic degradation of organic dyes [48]. The resulting composite had a high efficiency in the photodecomposition of dyes, while the CNT surface was densely covered and wrapped with Ag and SrTiO₃ nanoparticles.

Another distinctive advantage of the sol–gel method is the possibility of combining it with other methods, which is known as hybridisation. Various researchers have reported the successful hybridisation of sol–gel with other synthesis methods. Thus, a combination of sol–gel and hydrothermal methods was used for the synthesis of SrTiO₃ photocatalysts doped with La and Cr for hydrogen production [49,50]. Consequently, the composite obtained by the hybrid sol–gel hydrothermal method demonstrated excellent photocatalytic performance for the release of H₂ in the visible-light spectrum compared to another hybrid polymerised complex method [49]. Based on these studies, a highly porous Pt STO:C, N heterostructure was synthesised via a two-stage sol–gel method using a polymer in addition to a solvothermal method [51]. A distinctive feature of this technology is the production of mesopores inside the volume of cubic nanoparticles, whereas the specific surface area is attained owing to voids between nanoparticles in the previously described methods.

Precipitation/co-precipitation

Precipitation and co-precipitation are conventional methods for synthesising semiconductor heterostructures. Generally, a heterojunction based on SrTiO₃ is obtained through a reaction in a liquid solution with SrTiO₃, dropwise addition of the second component to the solution, and pH adjustment, followed by mixing and precipitate formation. Thus, a SrTiO₃@Ag@Ag₃PO₄ photocatalyst was obtained via precipitation, wherein Ag₃PO₄ nanoparticles had a spherical shape with an average diameter of 50–100 nm and were uniformly grown on the acicular surface of SrTiO₃ particles, which were obtained using the hydrothermal method. Compared with pure SrTiO₃ and Ag₃PO₄, the synthesised sample demonstrated excellent photocatalytic activity for tetracycline photodegradation [52]. Similarly, an N–SrTiO₃/BiOBr heterostructure was obtained with a flake nanoparticle morphology; irregularly shaped N–SrTiO₃ nanoparticles (size = 20–30 nm) formed a close interfacial contact with the BiOBr nanosheets, which facilitated rapid separation and improved the transport of photogenerated electrons and holes between N–SrTiO₃ and BiOBr [53].

The photocatalytic efficiency of SrTiO_3 and other types of photocatalysts can be considerably improved by forming a morphology with a large specific surface area, which increases the number of active centres. Thus, the formation of the $\text{Ag}_3\text{PO}_4/\text{SrTiO}_3$ composite by the deposition of homogeneous Ag_3PO_4 nanoparticles on the surface of SrTiO_3 nanofibres increases the photocatalytic activity by 10 times compared with that of pure SrTiO_3 in the visible light range [54].

Other methods for obtaining heterostructured SrTiO_3 -based photocatalysts

In addition to the above-mentioned methods, other methods include the chemical reduction [55,56], impregnation [57], polymer precursor [58,59], low-temperature process [60], chemical vapour deposition [61], atomic layer deposition (ALD) [62], sequential ion layer adsorption reaction (SILAR) [63], and simple high-energy ultrasound [64] methods, which can be used to synthesise heterostructured nanocomposites, of which one component is SrTiO_3 ; these nanocomposites are used for various photocatalytic applications under the influence of visible light. However, all these methods have limitations that hinder their widespread practical application for the synthesis of SrTiO_3 -based heterojunctions. For example, a composite with Ag nanoparticles decorated on the acicular surface of SrTiO_3 particles was obtained via the ALD method; however, the complexity of mass production and prolonged deposition time are disadvantages of this method [62]. The SILAR method is a simple and cost-effective technology for producing ternary semiconductors. Accordingly, it has been used to obtain nanocomposite photocatalysts with a Z-scheme and H-type $\text{SrTiO}_3/(\text{BiFeO}_3@\text{ZnS})$, wherein SrTiO_3 nanoparticles (100 nm) are connected to elliptical BiFeO_3 nanoparticles (50 nm) coated with a ZnS nanofilm (thickness = 22 nm). The synergistic effect of the Z-scheme and heterojunction contributed to the high photocatalytic activity with a 2,4-dichlorophenol photodecomposition rate and Cr(VI) conversion of 91.32% and 97.87%, respectively. However, the relatively long synthesis duration is the primary disadvantage of this method [63]. Another promising production technology is the high-energy ultrasonic treatment method, which enables the synthesis of a heterostructured $\text{rGO}@\text{SrTiO}_3$ nanocomposite by dispersing graphene oxide and SrTiO_3 nanoparticles in a ternary solvent [64]. This method can be used to significantly reduce the size of crystallites and the band gap, enhance the optical properties of SrTiO_3 , and improve the morphology of SrTiO_3 and $\text{RGO}/\text{SrTiO}_3$ samples by increasing the specific surface area. The $\text{RGO}/\text{SrTiO}_3$ heterostructure photocatalyst exhibited degradation rates of 94.5% and 90% within 100 min with reference to rhodamine B (RhB) and Rose Bengal dyes, respectively.

The synthetic method used to prepare SrTiO_3 -based composites can have a significant impact on their performance. The choice of synthetic method can affect various characteristics of the composites, such as their composition, structure, morphology, surface area, and crystallinity. These factors, in turn, influence the photocatalytic activity, stability, efficiency, and selectivity of the composites. Different synthesis methods may result in variations in the size and distribution of SrTiO_3 particles, the presence of impurities or defects, or the

incorporation of dopants or additional components. These factors can influence the charge transfer, light absorption, and surface reactivity of the composites, ultimately affecting their photocatalytic performance.

Table 1 presents the methods used to develop various SrTiO_3 -based composites and the primary parameters of these composites that affect their performance. However, although the characteristics of the synthesised composites are successfully improved using these methods, all synthesis processes have been typically performed under laboratory conditions; consequently, commercialisation can be achieved only by introducing technology for the large-scale production of hybrid composite SrTiO_3 -based photocatalysts.

Application of heterostructured SrTiO_3 -based photocatalysts

Composites with SrTiO_3 -based heterojunctions are extensively used in the hydrogen, solar energy, and energy storage industries. In addition, the relatively high photocatalytic characteristics of SrTiO_3 -based composites, compared with those of pure components, are beneficial for producing bio-diesel and environmentally friendly hydrogen, purifying wastewater and the atmosphere from various pollutants (dyes, antibiotics, CO_2 , and NO), and sterilisation under the influence of electromagnetic radiation. The electrocatalytic and dielectric properties of SrTiO_3 -based composites have been used to fabricate high-performance solar cells [84,85], biosensors [86], and supercapacitors [87]. Graphic illustrations of different applications of SrTiO_3 -based composites are shown in Fig. 2.

Photocatalytic water splitting with the release of hydrogen

Photocatalytic water splitting with the release of hydrogen upon irradiation with sunlight is considered a promising technology owing to its environmental friendliness and low cost. This process primarily requires the photocatalyst, light energy, and water; the process essentially involves the decomposition of a water molecule into hydrogen and oxygen. Breaking the intermolecular bonds of water requires energy; for example, electrolysis requires electrical energy. Generally, upon irradiation, the photocatalyst absorbs a photon of energy to form an electron–hole pair, provided that the energy of the light is equal to or greater than the bandgap energy of the semiconductor. Consequently, the excited negatively charged electrons are transferred to the conduction band (CB), followed by the reduction of water and release of gaseous hydrogen. Simultaneously, a positively charged hole in the valence band (VB) oxidises water to form oxygen gas. The two conditions necessary for the photocatalytic decomposition of water into H_2 and O_2 under the influence of light are as follows.

- 1) The minimum photon energy for photoabsorption should be 1.23 eV;
- 2) The energy position of the CB of the photocatalyst is more negative than the redox potential H^+/H_2 (0 V versus normal hydrogen electrode (NHE) at pH = 0), and the energy

Table 1 – Recent methods for the development of various SrTiO₃-based composites and the main parameters of these composites that affect their performance.

Year	Photocatalyst	Synthetic Methods	Heterojunction	Structure	Particle size, nm	Band gap, eV	SSA, m ² /g	Ref
2022	Ag(x)STO/g-CN	Hydrothermal	Type II	nanoparticles	20–35 (SrTiO ₃)	2.72	298.12	[40]
2019	CdSe/SrTiO ₃	Hydrothermal	–	quasi-spherical	120.5	1.85	–	[37]
2021	SrTiO ₃ :La/Rh–BVO	Hydrothermal	Z-scheme	hollow multishell	90	2.4	8.232	[36]
2022	C-dots/SrTiO ₃ /NH ₄ V ₄ O ₁₀	Hydrothermal	Z-scheme	nanosheets	10.61 (C-dots)	2.54	29.6	[41]
2018	ZnO/SrTiO ₃	Hydrothermal	–	nanosheets/spherical	–	2.99(SrTiO ₃)	18.18	[38]
2019	SrTiO ₃ /TiO ₂	Hydrothermal	–	rod-like	80–120	3.04	–	[65]
2020	SrTiO ₃ /MnFe ₂ O ₄	Hydrothermal	Z-scheme	quasi-spherical	16.7 (SrTiO ₃)	2.2	14.49	[55]
2019	FTO/TiO ₂ /SrTiO ₃	Hydrothermal	Type II	nanoparticles	30–50 (SrTiO ₃)	3.24	–	[66]
2019	Co _{0.7} Zn _{0.3} Fe ₂ O ₄ –SrTiO ₃	Hydrothermal	Type II	quasi-spherical	20	2.89	27.82	[67]
2021	rGO/SrTiO ₃	Hydrothermal	–	spherical	33.1	3.1	–	[39]
2021	SrTiO ₃ –TiO ₂	Hydrothermal	Type II	spherical	250	–	58	[68]
2018	Pt/N–TiO ₂ /110T–SrTiO ₃	Hydrothermal	–	nanotube	66	–	298.3	[69]
2018	SrTiO ₃ – TiO ₂	Hydrothermal	–	hollow multi-shelled	45	3.3 (SrTiO ₃)	–	[35]
2019	SrTiO ₃ –T/CdZnS	Hydrothermal	–	nanoparticles	20	–	–	[70]
2019	Porous graphene/SrTiO ₃	Solvothermal	–	spherical	28.8	2.93	65.35	[44]
2019	SrTiO ₃ /BiOI	Solvothermal	p–n junction	nanofibers	30.43 (SrTiO ₃)	2.3	6.1	[43]
2019	Ag modified STO	Solvothermal	–	nanocubic	30 (SrTiO ₃)	3.28	27.51	[71]
2021	CSWT75	Solvothermal	Z–scheme	nanoparticles	5–100	3.15 (SrTiO ₃)	3.367	[72]
2019	SrTiO ₃ /N–GNS	Solvothermal	–	cylindrical	50	–	171.3	[73]
2021	Ag@SrTiO ₃ @CNT	Sol–gel	Schottky junction	spherical	21	2.7	78	[48]
2018	TiO ₂ –SrTiO ₃	Sol–gel	–	spherical	24.49	2.75	126.8	[45]
2022	SrTiO ₃ /CoAlMnO ₄	Sol–gel	Type I	core-shell	20	2.4	–	[46]
2021	SrTiO ₃ /SrSO ₄ /Pt	Sol–gel	–	cubic	100 (SrTiO ₃)	3.2	–	[47]
2018	SrTiO ₃ /TiO ₂	Sol–gel	–	nanoparticles	680	3.03	21.4	[74]
2018	SrTiO ₃ (La,Cr)	Sol–gel–hydrothermal	Z-scheme	nanoparticles	10–50	2.52	20.6	[49]
2019	SrTiO ₃ (La,Cr)–6	Sol–gel–hydrothermal	–	spherical	30–80	–	17.9	[50]
2021	ZSTO, AZSTO	Sol–gel–electrospinning	p–n junction	nanofibrous	210	2.49	30.4	[75]
2018	Pt/STO:C,N	Polymer–assisted sol–gel	Schottky junction	nanocuboid	90–100	2.97	176	[51]
2020	SrTiO ₃ /Ag/Ag ₃ PO ₄	Precipitation	Z-scheme	urchin-like	several μ m	3.12 (SrTiO ₃)	–	[52]
2020	N–SrTiO ₃ /BiOBr	Precipitation	Type II	spherical	20–30	2.71	8.05	[53]
2018	Ag ₃ PO ₄ /SrTiO ₃	Precipitation	–	nanowires	100–200	–	–	[54]
2021	C–SrTiO ₃ /PAN/WS–FLG	Electrospinning	–	microfibers	200–400	2.72	2760	[76]
2018	SrTiO ₃ @Mo ₂ C	Electrospinning	Type I	core-shell nanofibers	120	3.23 (SrTiO ₃)	–	[77]
2018	Ag–SrTiO ₃	Electrospinning	–	nanofibers	≈ 191	1.68	48.92	[78]
2020	TiO ₂ /SrTiO ₃ /gC ₃ N ₄	Electrospinning and gas-solid reaction	Z-scheme	nanofibers	≈ 100	3.25 (SrTiO ₃)	46.7	[79]
2020	SrTiO ₃ /Ag	ALD	–	urchin-like	150	–	129.7	[62]
2018	RGO/SrTiO ₃	High energy ultrasonication	–	cubic	53	2.87	31	[64]
2020	SrTiO ₃ /(BiFeO ₃ @ZnS)	SILAR	Z-scheme and H-type	cubic	100 (SrTiO ₃)	3.3(SrTiO ₃)	–	[63]
2019	gC ₃ N ₄ /SrTiO ₃	Mechanically milling and calcination	Type II	cubic	≈ 150–180	3.16 (SrTiO ₃)	32.4	[80]
2020	Pt/STO	Chemical reduction	Schottky junction	coral-like	≈ 30–50	3.26 (SrTiO ₃)	–	[40]
2021	CuPd/SrTiO ₃ –CuPd–Bi ₂ O ₃	Chemical reduction and high temperature calcination	Z-scheme	spherical	25 (SrTiO ₃)	3.2 (SrTiO ₃)	–	[17]
2018	pGCN–ST	Impregnation	–	cubic	25	2.76	83.3	[57]
2022	SrTiO ₃ /Ag ₂ O–NDC	Polymeric precursor	–	cubic	20–30 (SrTiO ₃)	2.84	247.32	[58]
2020	SrTiO ₃ /g–C ₃ N ₄	Polymeric precursor	Type II	nanoparticles	32–45 (SrTiO ₃)	2.7	37	[59]
2018	SrTiO ₃	Hydrothermal	–	nanoparticles	20–40	–	33.1	[29]

2017	SrTiO ₃	Sol-gel	—	spherical	10	—	—	[30]
2018	SrTiO ₃	Hydrothermal	—	cubic	1000	3.063	—	[81]
2022	SrTiO ₃	Hydrothermal	—	nanofibers	6000 in length	—	14.38	[28]
2020	SrTiO ₃	Hydrothermal	—	cubic	35–40	3.29	27.43	[27]
2020	SrTiO ₃	Solvothetmal	—	golf-like, star-like, urchin-like and flower-like	97, 390, 530, 1500	3.11, 3.08, 3.08, 3.06	20, 70.3, 106.6, 115.9, 131.8	[82]
2020	SrTiO ₃	Solvothetmal	—	ribbon-like	120–170	—	—	[83]
2021	SrTiO ₃	Sol-gel	—	cubic	22	—	—	[31]
2019	SrTiO ₃	Sol-gel–solid phase	—	nanocrystalline	34	3.173	—	[34]
2022	SrTiO ₃	Co-precipitation	—	spherical	50.07	3.241	20.971	[32]

position of the VB is more positive than the redox potential O₂/H₂O (1.23 V versus NHE at pH = 0).

The SrTiO₃ semiconductor has a wide band gap of 3.2 eV, which contributes to the photoinduction of electrons and holes under UV light irradiation ($\lambda \leq 387.5$ nm); the CB and VB potentials are -0.61 and 2.59 eV, respectively. Therefore, owing to its redox potential, SrTiO₃ is a suitable material for photocatalytic water decomposition [88]. However, owing to its wide band gap and consequently low efficiency, pure SrTiO₃ requires modification with oxides of metals, non-metals, and other semiconductors, thereby forming heterojunctions and composites. The photocatalytic characteristics of SrTiO₃-based heterojunctions for hydrogen production are improved to increase the light absorption spectrum by decreasing the recombination of photogenerated electron–hole pairs. The efficient separation and transfer of charge carriers is crucial in SrTiO₃-based heterojunctions. Incorporating other materials like graphene into the SrTiO₃ structure enhances the efficiency of charge separation. The presence of a heterojunction between SrTiO₃ and another material provides additional pathways for charge transfer. Photogenerated electrons can move to the conduction band of the co-catalyst material, while photogenerated holes can be effectively captured by SrTiO₃. This spatial separation reduces recombination of the charges, leading to higher overall efficiency in the photocatalytic process.

Currently, nanocomposite semiconductor photocatalysts based on SrTiO₃ are widely used for releasing H₂ through the photocatalytic decomposition of water upon visible-light irradiation. The efficiency of heterostructured composite photocatalysts can be improved by the synergistic effect of several combined components. Particularly, this effect is observed in the STO–TiO₂NTs@Au composite, which demonstrates excellent photocatalytic efficiency for water decomposition, with a high hydrogen evolution rate under artificial solar radiation ($7200 \mu\text{mol h}^{-1}\text{g}^{-1}$) [89]. This high efficiency is attributed to the possible synergistic effect of the STO–TiO₂NTs@Au structure itself, because the synthesised composite facilitates the charge carrier separation and increases the oxidation potential of Au nanoparticles. Furthermore, the SrTiO₃–T/Cd_{0.5}Zn_{0.5}S nanocomposite demonstrates the highest rate of photocatalysis with H₂ release, that is, $25.01 \text{ mmol h}^{-1}\text{g}^{-1}$ in the visible light spectrum [70]. In this case, the high efficiency is attributed to the high concentration of oxygen vacancies on the SrTiO₃ nanocrystal surface, which results in the effective separation of photoinduced charge carriers. A nanocomposite based on gC₃N₄/SrTiO₃ resulted in a considerably high efficiency of hydrogen production via water decomposition under visible light (hydrogen formation rate = $966.8 \mu\text{mol h}^{-1}\text{g}^{-1}$), owing to the effect of interfacial coupling between g-C₃N₄ and SrTiO₃ [80].

Doping SrTiO₃ with metals subsequently increases the light absorption capacity in the visible spectrum because the band gap of the semiconductor is narrowed by the creation of a d-level in the middle of the band gap. However, phase impurities formed during doping can serve as recombination sites for photoinduced electrons and holes, thereby suppressing the electrical conductivity and reducing the photocatalytic efficiency. Despite this, numerous studies have



Fig. 2 – Various applications of SrTiO₃-based composites.

demonstrated the successful use of metals in heterostructured composites based on SrTiO₃. For example, the composite photocatalyst Au–Al/SrTiO₃ demonstrates a high hydrogen evolution rate ($347 \mu\text{mol h}^{-1}\text{g}^{-1}$) under illumination in the visible light range, and this is associated with the effect of the Au–Al pair on light absorption [90].

In contrast, doping SrTiO₃ with non-metals such as N and C is more practical and beneficial for several reasons. First, N^{3–} ions, which partially replace (O^{2–}) in the oxide lattice, do not significantly contribute to the exciton recombination process. Second, the band gap of the semiconductor is narrowed owing to the overlap of the p-state with oxygen 2p-orbitals, which ultimately improves the photocatalytic performance under visible light. For example, the mesoporous Pt/SrTiO₃:C,N photocatalyst used for water splitting exhibited an excellent hydrogen formation rate ($3400 \mu\text{mol h}^{-1}\text{g}^{-1}$) under UV/visible light, with reliable stability during 15 h of irradiation [51].

The shape of the heterostructure is another important factor that affects the increase in the photocatalytic activity. For example, using a heterostructured nanocomposite in the form of one-dimensional SrTiO₃@2Mo₂C nanofibres with a core and shell, the hydrogen evolution rate was increased by 15 times compared with that of the initial SrTiO₃, upon irradiation with sunlight [77]. The closed heterostructure and high electrical conductivity of Mo₂C improve the light absorbing capacity and phase conductivity and prevent the recombination of the generated charge carriers, facilitating the transfer of photogenerated electrons and holes to active centres. Tubular photocatalysts are also of considerable interest. The nanotubular multijunction photocatalyst Pt/N–TiO₂@SrTiO₃ exhibited excellent efficiency with a hydrogen production rate of $3873 \mu\text{mol h}^{-1}\text{g}^{-1}$ under the influence of sunlight [69]. The 150T-SrTiO₃ sample had a specific area of $298.3 \text{ m}^2 \text{ g}^{-1}$ and an average nanotube diameter of 66 nm, with well-dispersed square SrTiO₃ particles (diameter = 52–66 nm) [120]. A similar surface area ($300 \text{ m}^2 \text{ g}^{-1}$), but with a scaly shape, was successfully obtained during synthesis of the triple heterostructure SrTiO₃@TiO₂/C by freeze-casting in a mixture with

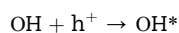
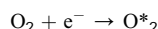
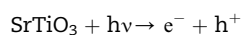
colloidal silica as a solid template and combining hierarchically lined (micro-, meso-, and macro-) pores [91]. Under UV irradiation, the synthesised SrTiO₃/TiO₂/C sample exhibited the optimal photocatalytic activity for H₂ evolution at a rate of $2.52 \text{ mmol h}^{-1}\text{g}^{-1}$, which is 1.5 times higher than that of the reference P25 photocatalyst.

Based on the above-mentioned studies, although pure SrTiO₃-based photocatalysts are considered inefficient, the careful design and creation of SrTiO₃-based composites can increase the photocatalytic activity for hydrogen production during the photocatalytic decomposition of water under solar radiation. The photocatalytic efficiency of SrTiO₃-based composites can be increased because of a combination of several factors, such as: 1) providing an improved specific surface area to create numerous reaction centres; 2) narrowing the band gap by synthesising wide-gap SrTiO₃ and narrow-gap semiconductors or using metals to increase light absorption in the UV–visible region; 3) doping with metals and non-metals, inclusion of oxygen vacancies on the SrTiO₃ nanoparticle surface, and creation of a heterojunction to prevent recombination of photogenerated electron–hole pairs; 4) deposition of the desired type of co-catalyst to provide a driving force between the redox potential of H₂O and H₂.

Photocatalytic decomposition of organic pollutants and antibiotics

The use of photocatalysts for organic pollutant decomposition has attracted particular attention in recent years because it involves solar energy, which is inexhaustible, environmentally friendly, and affordable. Recent studies have demonstrated the effect of using various types of photocatalysts for decomposing hydrocarbons [92], dyes [44,93,94], pesticides [40,58], carboxylic acids [95,96], antibiotics [41,97], and other organic pollutants [98,99]. According to the principle of photocatalysis, as described previously, light irradiation with energy equal to or greater than the band gap of the photocatalyst consequently forms holes (h⁺) in the VB as electrons

are photoexcited into the CB. The photoexcited electrons allow the O_2 reduction reactions to proceed until highly reactive radicals are formed. The holes, which are simultaneously excited in the VB, oxidise H_2O into highly reactive hydroxyl radicals. The induced active radicals and the photoexcited holes accelerate the decomposition of the adsorbed organic pollutant particles. However, active photo-generated charge carriers also decompose the pollutant molecules. The main stages of the decomposition process upon light irradiation are as follows [31]:



Among the numerous photocatalysts, $SrTiO_3$ is one of the most suitable candidates for the photocatalytic decomposition of organic pollutants because of its high photoactivity, thermal and chemical stability, low cost, non-toxicity, and environmental friendliness [31]. As specified in the previous section, pure $SrTiO_3$ absorbs light only in the UV spectrum owing to its wide bandgap (3.2 eV) and rapid recombination of photogenerated carriers. The modification of $SrTiO_3$ and development of photocatalyst heterojunctions are effective solutions for expanding the absorption region towards the visible spectrum. In addition, the charge separation process in $SrTiO_3$ -based heterojunctions is crucial for efficient photocatalytic degradation of organic pollutants and antibiotics. By creating heterojunctions with other materials, such as graphene or metal oxides, the charge separation efficiency can be enhanced. In these heterojunctions, the photogenerated electrons in $SrTiO_3$ can transfer to the conduction band of the co-catalyst material. This facilitates the rapid separation of charge carriers and minimizes their recombination, which would otherwise reduce the overall photocatalytic activity. For example, a complex composite photocatalytic system, $SrTiO_3@Bi_5O_7I$, can be used to decompose an RhB solution upon irradiation with artificial sunlight [100]. Using 30 wt% $SrTiO_3@Bi_5O_7I$ nanocomposite, dye degradation reaches 89.6% within 150 min of photocatalysis. However, this result is not the most efficient; the $SrTiO_3@Fe_2TiO_5$ composite modified with CNTs shows unique photocatalytic performance in the complete decomposition of the methylene blue (MB) dye within 71 min, whereas MO and RhB dyes are degraded by 64% and 89%, respectively, in the same duration [101]. This can be explained by the improvement in the photocatalytic characteristics of $SrTiO_3$ owing to CNTs, thereby promoting the efficient separation of electrons and holes and minimising the recombination rate of photogenerated charge carriers. In addition, increasing the specific surface area of the resulting system improves the visible-light absorption. Furthermore, including CNTs in the system can contribute to the photosensitization of semiconductor particles, because electron–hole pairs are generated on their surface [102].

For water decomposition with hydrogen evolution, comprehensively understanding the effect of the morphology of photocatalysts on their activity can help to improve the photocatalytic purification of water from organic pollutants. One such example is the highly efficient $Co_{0.7}Zn_{0.3}Fe_2O_4-SrTiO_3$ nanocomposite with an improved pore hierarchy and core–shell structure [67]. Additionally, studies have shown that $Co_{0.7}Zn_{0.3}Fe_2O_4-SrTiO_3$ has a high photodecomposition rate for the Congo red dye ($5.08 \times 10^{-1} \text{ min}^{-1}$) owing to the core–shell structure, chemical behaviour of the dye, and increased hierarchy of photocatalyst pores. The generation of charge carriers on the surface of a nanomaterial owing to the piezoelectric effect can produce free radical groups for organic pollutant degradation. Combining a piezoelectric material with a photocatalytic semiconductor effectively improves the photocatalytic characteristics of composites [97,103,104]. The $SrTiO_3$ photocatalyst is an effective material for obtaining such nanocomposite structures. For example, heterogeneous $BaTiO_3/SrTiO_3$ nanocomposites in the form of fibres demonstrate highly efficient and rapid photodecomposition of RhB (~97.4% in 30 min) under simultaneous exposure to ultrasound and UV. The high efficiency is attributed to the piezoelectric effect, which decreases the bandgap and provides a built-in polarisation field, thereby facilitating the separation of photoinduced electrons and holes [105].

Antibiotics and pharmaceuticals (such as carbamazepine (SMX) [106], aureomycin hydrochloride (CTC•HCl) [41], ciprofloxacin (CIP) [107], and tetracyclines (TCs) [108,109], are other pollutants in wastewater that severely affect human health, owing to their toxicity and chemical stability. This problem can potentially be solved through the photocatalytic degradation of antibiotics under light irradiation. Despite the high efficiency of several photocatalytic systems with reference to antibiotic decomposition, most systems are based on UV irradiation, which significantly limits their use in vivo [55]. However, heterostructured photocatalysts have recently been synthesised and demonstrate high efficiency in wider radiation spectra; examples include the heterojunction composite CSWT75 based on the Z-scheme (100% decomposition of TC rings B, C, and D in 60 min and 98% decomposition of the A ring of TC in 90 min) [72], ZSTO nanofibre membranes modified with silver phosphate (85% decomposition of tetracycline hydrochloride in 60 min) [75], and triple C-dots/ $Cu_2O/SrTiO_3$ composites (92.6% decomposition of chlortetracycline hydrochloride in 90 min) [110]. The above-mentioned photocatalysts are suitable for only one type of antibiotic, whereas in another study [41] a new Z-scheme heterojunction of $SrTiO_3/NH_4V_4O_{10}$ decorated with C-dots was developed for the simultaneous decomposition of SMX, CTC•HCl, and CIP under artificial sunlight irradiation; the photocatalyst demonstrated efficiencies of 94.7, 88.3, and 86.05%, respectively, without significant inactivation after four treatment cycles.

Creation of heterojunctions, doping, surface modification, and metal/non-metal deposition are employed to improve the efficiency of composite $SrTiO_3$ -based photocatalysts for the photocatalytic degradation of various organic pollutants and antibiotics. Consequently, 1) the band gap width is reduced, leading to photoabsorption in the visible radiation spectrum;

2) VB and CB are optimally arranged, thereby suppressing the recombination of photoinduced e^-/h^+ pairs; 3) unique, flexible, and nanoscale surfaces are created to facilitate the transfer of charge carriers to the photocatalyst surface; 4) sufficiently hierarchical porosity is generated to allow the substance to penetrate into the interior and provide multiple reaction centres for the redox process; 5) the photocatalysts can possibly be reused. Because environmental problems are a cause for concern, and considering the above-mentioned studies on the use of photocatalysts for the effective decomposition of organic pollutants and antibiotics, modified SrTiO_3 -based composites are promising photocatalysts for environmental and health applications.

Photocatalytic decomposition of organic air pollutants

Global environmental problems associated with excessive CO_2 emissions are detrimental to the planet. In this regard, researchers have investigated the reduction of CO_2 and its conversion into organic fuel in the presence of semiconductor photocatalysts [111–113]. The mechanism for photocatalytic reduction of air pollutants is similar to photocatalytic water purification, but with a slight difference. In the case of photocatalytic reduction of CO_2 , the photogenerated electrons on the surface of the photocatalyst interact with the adsorbed CO_2 molecules, resulting in their conversion into hydrocarbons or other valuable chemical compounds. This process involves the transfer of electrons from the photocatalyst to CO_2 , effectively transforming CO_2 into a more useful form. Recently published reports on the photoreduction of CO_2 to CO emphasise that the photocatalytic efficiency is affected by the ability of the photocatalyst to adsorb CO and light, and the rapid separation and transport of photogenerated charge carriers [114,115]. The use of SrTiO_3 -based composites has also attracted considerable interest for CO_2 photorecovery and organic pollutant decomposition. Thus, the $\text{SrCO}_3/\text{SrTiO}_3$ heterostructure demonstrates a sufficiently high rate of CO formation $\sim 23.82 \text{ mmol h}^{-1}\text{g}^{-1}$, which is ~ 11.34 and ~ 6.75 times higher than those of pure SrTiO_3 and SrCO_3 , respectively [116]. The SrTiO_3 heterojunction photocatalyst decorated with Ag nanoparticles can also be used to produce hydrogen [71]. This composite demonstrates high photoactivity, reducing CO_2 to CO ($80.24 \text{ mmol g}^{-1}$), and the rate of H_2 release is $264.5 \text{ mmol h}^{-1}\text{g}^{-1}$. Such high rates are associated with the influence of Ag nanoparticles, which contribute to the passage of localised surface plasmon resonance (LSPR). Owing to the synergistic effect of the photocatalytic activity and LSPR of the resulting composite, it can be used both for CO_2 reduction and hydrogen production. Furthermore, heterostructured SrTiO_3 -based photocatalysts have been used to remove NO, which is harmful to the environment and human life [117,118]. The SrTiO_3 photocatalyst is promising for removing NO, and decorating it with a co-catalyst composed of inexpensive SrCO_3 eco-material avoids disadvantages such as catalyst poisoning and rapid recombination of photoinduced electrons and holes. For example, the $\text{SrCO}_3/\text{SrTiO}_3$ composite with a band gap of 2.9 eV exhibited optimal photoactivity when 47% NO was removed after 12 min of artificial sunlight irradiation [119]. In another similar study, a heterostructured Bi/ SrTiO_3 photocatalyst, synthesised via a simple sol–gel method, was

used to achieve a high photocatalytic activity, with 37% NO removal efficiency during 10 min of visible light irradiation [120].

Photocatalytic sterilisation

Semiconductor photocatalysts are promising materials for sterilisation owing to their characteristics, such as high oxidisability, non-toxicity, photostability, and chemical resistance [121]. Photocatalysts have the capability to generate reactive oxygen species (ROS), like hydroxyl radicals ($\cdot\text{OH}$), which possess powerful oxidative properties when they interact with photons. When microorganisms come into contact with the surface of the photocatalyst, these ROS can initiate attacks on their cell membranes, proteins, and DNA, causing damage. This oxidative stress ultimately results in the sterilisation or deactivation of the microorganisms. Nanocomposite semiconductor photocatalysts based on SrTiO_3 can be used as bactericidal or antimicrobial systems under suitable light irradiation. Typically, photocatalytic sterilisation occurs because of the synthesis of antibacterial materials and SrTiO_3 and the creation of a composite with a heterojunction; the photoabsorption area of SrTiO_3 can be expanded to the visible light spectrum. In SrTiO_3 -based heterojunctions, an interface is created between SrTiO_3 and another material. This interface aids in the separation of electron-hole pairs generated by light. Electrons move towards the surface of the photocatalyst, while holes either stay within the bulk material or diffuse towards the surface of the other material. Such hybrid composites are widely used for the inhibition and sterilisation of *Escherichia coli* (*E. coli*) and *Staphylococcus aureus* (*S. aureus*) [75,110,122–124]. For example, a nanocomposite structure of polydopamine-functionalized (PDA) SrTiO_3 gallium-doped nanotubes (PDA– SrTiO_3NT) was synthesised and studied for stability in vivo. The PDA– SrTiO_3 NT sample retained approximately 72% of its antibacterial activity for 14 days and could sterilize both *E. coli* and *S. Aureus* [122]. Another composite photocatalyst $\text{Cu}_x\text{O}/\text{Ag}/\text{SrTiO}_3$ designed in the form of a Z-scheme, is highly effective in removing toluene and *E. coli* because of the presence of Ag nanoparticles and Cu^+ [123].

However, compared with these heterostructured composites, triple C-dots/ $\text{Cu}_2\text{O}/\text{SrTiO}_3$ exhibit the highest efficiency, with a photocatalytic inactivation of 91.58% for 60 min with reference to *E. coli* under sunlight; however, under the same conditions, the results were extremely low for pure Cu_2O and SrTiO_3 . The photocatalytic characteristics were primarily optimised by the synergy of the p–n heterojunction and the introduction of carbon quantum dots, which promoted the separation and migration of charge carriers and improved the absorption capacity in the longer-wavelength light spectrum of the photocatalysts [110].

Other applications of heterostructured SrTiO_3 -based photocatalysts

Photoanodes for dye-sensitized solar cells

In contrast to conventional semiconductor solar cells, dye-sensitized solar cells (DSSC) convert solar energy into electricity at relatively low costs, demonstrating adequate

efficiency. The primary components of traditional DSSC are the photoanode, electrolyte, and anti-electrode [125]. Consequently, most of the studies aimed at improving the efficiency of DSSC have concentrated on modernising the photoanode. The photoanode materials are mesoporous semiconductors, such as SnO_2 , Nb_2O_5 , WO_3 , and TiO_2 , deposited on a transparent electrically conductive electrode, and light-sensitive dye molecules adsorbed on the semiconductor surface. When irradiated with light, the dye molecule, which absorbs photons, generates an electron in the CB and is directed along an external circuit. From the electrolyte, an electron from the iodine ion (I^-) regenerates the excited dye molecule, oxidising it to the triiodide ion (I_3^-), which in turn is regenerated by an electron from the counter electrode.

One reason for the decrease in the efficiency of DSSC is the rapid recombination of charge carriers produced by the photosensitive dye [125]. Because all the induced electrons do not reach the photoanode, the magnitude of the photocurrent is not proportional to the number of excited electrons. To solve this problem, many studies have used a blocking layer that suppresses the charge carrier recombination and consequently increases the efficiency of DSSC. Perovskite SrTiO_3 is a promising material for blocking layers. Heterostructured SrTiO_3 -based photocatalysts are promising materials for creating highly efficient photoanodes for DSSC. For example, the hetero-structured composite $\text{SrTiO}_3/\text{TiO}_2$ exhibits a photocatalytic conversion efficiency of 2.68%, which is 38% higher than that of pure TiO_2 (1.93%). Electrochemical impedance spectroscopy results indicate that the improved efficiency of DSSC is because of an increase in the charge lifetime and resistance of electron transport in the photoanode owing to the presence of SrTiO_3 in the blocking layer [65]. In two-layer DSSC photoanodes composed of 0.05% AC/TiO_2 and SrTiO_3 composites, the second layer of SrTiO_3 improved the photovoltaic characteristics by reducing the recombination of charge carriers at the interface, and a similar band structure increased the electron lifetime, thereby increasing J_{SCs} and V_{OC} . In addition, the efficiency of DSSC increased by ~57% compared with that of a device consisting of TiO_2 [126]. In another study, SrTiO_3 nanoparticles synthesised via co-precipitation were used as photoanodes in quantum dot solar cells (QDSCs). The QDSCs constructed from a hetero-structured composite $\text{SrTiO}_3/\text{CDs}/\text{Bi}_2\text{S}_3/\text{ZnS}:\text{Cu}$ demonstrated a maximum current of 2.38 mA cm^{-2} and a voltage (V_{OC}) of 0.37 V [127].

Electrochemical sensors/biosensors

Currently, the manufacture of SrTiO_3 -based nanostructures for use in electrochemical sensors and biosensors is an urgent research area. SrTiO_3 -based composites improve the electrocatalytic characteristics in terms of detecting necessary molecules. A hybrid $\text{SrTiO}_3/\text{N-GNS}$ nanocomposite has been used for the simultaneous determination of diphenhydramine (DPH) and bromhexine (BRO). The creation of a mesoporous heterojunction with nitrogen-doped graphene (N-GNS), which has excellent conductivity, subsequently generates numerous reaction centres in SrTiO_3 and improves its electrocatalytic characteristics. An electrochemical sensor based on $\text{SrTiO}_3/\text{N-GNS}$ demonstrates a wide dynamic range of $0.038\text{--}100.0 \text{ }\mu\text{M}$ for DPH and $0.030\text{--}90.0 \text{ }\mu\text{M}$ for BRO in a phosphate-buffered

Table 2 – The results of recent studies (2018–2022) on the use of SrTiO_3 -based heterostructured photocatalysts nanoparticles in the H_2 production application.

Year	Photocatalyst	Light Source	Sacrificial Agents	Efficiency, $\mu\text{mol h}^{-1}\text{g}^{-1}$	Ref.
2018	$\text{SrTiO}_3/\text{Mo}_2\text{C}$	300 W Xe lamp, 313 nm	25 mg catalyst, 90 mL of $\text{H}_2\text{O}/(10 \text{ vol}\%)$ TEOA	7900	[77]
2018	$\text{Pt}/\text{N-TiO}_2/110\text{T-SrTiO}_3$	310 W/m^2 Xe lamp, simulated sunlight	50 mL solution containing 25% v/v methanol	3873	[69]
2018	$\text{Au-Al}/\text{SrTiO}_3$	150 W Xe lamp, simulated sunlight	2.5 mg catalyst, 1000 mL of $\text{H}_2\text{O}/30\%$ isopropyl alcohol	347	[90]
2018	Pt-STO-C:N	300 W Xe lamp, 360 nm	20 mg catalyst, 50 mL of $\text{H}_2\text{O}/20\%$ v/v methanol	3400	[51]
2018	$\text{SrTiO}_3\text{--TiO}_2$	300 W Xe lamp, >400 nm	50 mg catalyst, 150 mL of DI $\text{H}_2\text{O}/\text{H}_2\text{PtCl}_6$ solution (0.73 mg/mL)	212	[35]
2018	$\text{SrTiO}_3\text{--TiO}_2$	300 W Xe lamp, >420 nm	100 mg catalyst, 200 mL of $\text{H}_2\text{O}/\text{NaI}$ (2 mmol L^{-1})	91	[49]
2018	$\text{ZnO}/\text{SrTiO}_3$	300 W Xe lamp	50 mg catalyst, 100 mL of $\text{H}_2\text{O}/\text{Na}_2\text{S--Na}_2\text{SO}_3$ (0.43:0.5)	263.49	[38]
2019	$\text{SrTiO}_3\text{--T}/\text{Cd}_{0.5}\text{Zn}_{0.5}\text{S}$	300 W Xe lamp, 420 nm	50 mg catalyst, 100 mL of $\text{H}_2\text{O}/(0.25\text{M Na}_2\text{S and } 0.35\text{M Na}_2\text{SO}_3)$	25,010	[70]
2019	$\text{gC}_3\text{N}_4/\text{SrTiO}_3$	300 W Xe lamp, 420 nm	50 mg catalyst, 100 mL of $\text{H}_2\text{O}/(10 \text{ vol}\%)$ TEOA	966.8	[80]
2019	$\text{SrTiO}_3/\text{TiO}_2/\text{C}$	300 W Xe lamp, >420 nm	100 mg catalyst, 100 mL of $\text{H}_2\text{O}/20\%$ v/v methanol	2520	[91]
2019	$\text{CdSe}/\text{SrTiO}_3$	300 W Xe lamp	25 mg catalyst, 100 mL of $\text{H}_2\text{O}/(0.35\text{M Na}_2\text{S, } 0.25\text{M Na}_2\text{SO}_3)$	418.75	[37]
2019	$\text{SrTiO}_3/\text{PAN}$	40 W UV lamp, 320 nm	10 wt% catalyst in $\text{H}_2\text{O}/20 \text{ vol}\%$ CH_3OH solution	305.9	[135]
2019	$\text{CdS}/\text{SrTiO}_3$	300 W Xe lamp, AM 1.5 cut-off filter	20 mg catalyst, 80 mL of $\text{H}_2\text{O}/10\%$ v/v methanol	1322	[136]
2020	$\text{STO-TiO}_2\text{NTs@Au}$	300 W Xe lamp, Simulated sunlight	30 mg catalyst, 80 mL of $\text{H}_2\text{O}/10\%$ v/v methanol	7200	[89]
2020	$\text{TiO}_2/\text{SrTiO}_3/\text{gC}_3\text{N}_4$	300 W Xe lamp, AM 1.5 cut-off filter	15 mg catalyst, 30 mL of $\text{H}_2\text{O}/10\%$ v/v methanol	1304	[137]
2020	$\text{Pt}/\text{gC}_3\text{N}_4/\text{SrTiO}_3$	500 W xenon lamp, >500 nm	1 g/L catalyst, 25% TEOA	471	[60]
2021	$\text{SrTiO}_3\text{:La}/\text{Rh}$	300 W Xe lamp, >400 nm	100 mg catalyst, 100 mL of $\text{H}_2\text{O}/20\%$ v/v ethanol	462	[36]
2021	$\text{C--SrTiO}_3/\text{PAN}/\text{WS-FLG}$	120 W UV lamp, 254 nm	1 g catalyst, 20 mL of $\text{H}_2\text{O}/15\%$ methanol	5375	[76]
2021	$\text{SrTiO}_3/\text{SrSO}_4/\text{Pt}$	300 W Xe lamp	50 mg catalyst, 10% v/v methanol	396.82	[138]
2022	$\text{Ag}_{(3)}\text{ STO}/\text{g-CN}$	300 W Xe lamp, 420 nm	50 mg catalyst, 100 mL of $\text{H}_2\text{O}/(0.35 \text{ mol L}^{-1} \text{ Na}_2\text{S } 9\text{H}_2\text{O and } 0.25 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_3)$	645.62	[40]

Table 3 – The results of recent studies (2018–2022) on the use of SrTiO₃-based heterostructured photocatalysts nanoparticles in the environmental remediation application.

Year	Photocatalyst	Organic Pollutant	Light Source	Irradiation Time	Efficiency	Ref.
2018	SrTiO ₃ /Bi ₅ O ₇ I	Rhodamine B	300 W Xe lamp	150 min	89,60%	[100]
2018	SrTiO ₃ /graphene	Rhodamine B	350 W Halogen lamp, 300–400 nm	70 min	97,60%	[139]
2019	CaO/SrTiO ₃	Rhodamine B	11 W UV light, 254 nm	120 min	92,50%	[140]
2021	BaTiO ₃ /SrTiO ₃	Rhodamine B	30 W, LED UV lamp, 365 nm	30 min	97,40%	[105]
2020	N–SrTiO ₃ /BiOBr	Rhodamine B	300 W Xe lamp, 400 nm	60 min	100%	[53]
2020	SrTiO ₃ /Ag	Rhodamine B	300 W Xe lamp	90 min	92,50%	[62]
2018	RGO/SrTiO ₃	Rhodamine B; Rose Bengal	sunlight	100 min	94.5; 90%	[64]
2018	Ag–SrTiO ₃	Rhodamine B; Methylene blue	visible light	60 min	93,5%; 94,7%	[78]
2019	SrTiO ₃ /TiO ₂	Methylene blue	High-power LED, 365 nm	220 min	100%	[66]
2018	PTh–SrTiO ₃	Methylene blue	250 W visible lamp	210 min	90%	[141]
2019	Porous graphene–SrTiO ₃	Methylene blue	250 W Hg, 410–700 nm	120 min	92%	[44]
2021	CuPd/SrTiO ₃ –CuPd–Bi ₂ O ₃	Methylene blue	300 W Xe lamp	4 h	93.87%	[17]
2021	Ag@SrTiO ₃ @CNT	Methylene blue; Methyl orange; Rhodamine B	150 W OSRAM lamp, <420 nm	30 min	100%; 71%; 46%	[48]
2022	SrTiO ₃ /Fe ₂ TiO ₅ /CNT	Methylene blue; Methyl orange; Rhodamine B	150 W visible light lamp	71 min	97%; 64%; 89%	[101]
2020	SrTiO ₃ /g–C ₃ N ₄	Methylene blue; Drug amiloride	visible light	420 min	1.3*10 ^{–3} (min ^{–1}); 1,82*10 ^{–3} (min ^{–1})	[59]
2021	rGO/SrTiO ₃	Methylene blue; 2-nitrophenol	500 W Halogen lamp	150 min	91%; 81%	[39]
2019	Co _{0.7} Zn _{0.3} Fe ₂ O ₄ @SrTiO ₃	Congo Red; Methylene blue	Halogen lamp	12min; 60 min	94,9%; 91,8%	[67]
2019	SrTiO ₃ /BiOI	Methyl orange	250 W metal ha lamp, >400 nm	3 h	94,60%	[43]
2018	La–WO ₃ /SrTiO ₃	Methyl orange	300 W Xe lamp, 420 nm	75 min	100%	[142]
2020	Pt/gC ₃ N ₄ /SrTiO ₃	Acid red 1	500 W xenon lamp >420 nm	120 min	83%	[60]
2018	pGCN–ST	Reactive blue 198; Reactive black 5; Reactive yellow 145	500 W tungsten lamp, 420 nm	120 min	100%	[57]
2022	SrTiO ₃ /CoAlMnO ₄	Erio Chrom Black T; Methylene Viole	300 W Xe lamp, ≥420 nm		92.42%; 90.34%	[46]
2020	SrTiO ₃ /PbBiO ₂ Br	Crystal violet	500 W Xe lamp	120 min	94,2	[143]
2021	SrTiO ₃ –TiO ₂	Cr ^{VI}	300 W Xe lamp, AM 1.5	4 h	100%	[68]
2020	SrTiO ₃ /(BiFeO ₃ @ZnS)	2,4-dichlorophenol	300 W Xe lamp	180 min	91.32%; 97.87%	[63]
2019	Ag–S–STO	4-chlorophenol	Solar light	120 min	96%	[144]
2022	SrTiO ₃ /Ag ₂ O–NDC	Dichlorodiphenyltrichloroethane	350 W Xe lamp, λ ≥ 420 nm	180 min	94,20%	[58]
2018	TiO ₂ /SrTiO ₃	4-nitrophenol	125 W mercury lamp, UV light	150 min	99%	[74]
2021	SrTiO ₃ /MnFe ₂ O ₄	Tetracycline	200 W Hg lamp, 253.7 nm	20 min	100%	[55]
2019	SrTiO ₃ (La,Cr)-6	Tetracycline	300 W Xe lamp, ≥420 nm	90 min	83%	[50]
2020	SrTiO ₃ /Ag/Ag ₃ PO ₄	Tetracycline	500 W Xe lamp >420 nm	15 min	72%	[52]
2021	CSWT75	Tetracycline	350 W Xe lamp	90 min	98%	[72]
2022	C-dots/SrTiO ₃ /NH ₄ V ₄ O ₁₀	SMX; CTC·HCl; CIP	500 W Xe lamp, >420 nm	120 min	94,7%; 88,3%; 86,05%	[41]
2022	SrCO ₃ /SrTiO ₃	CO ₂ to CO	300 W Xe lamp, λ ≥ 420 nm	–	23.82 μmol h ^{–1} g ^{–1}	[116]
2019	Ag modified SrTiO ₃	CO ₂ to CO	300 W Xe lamp, λ ≥ 420 nm	–	6.69 μmol h ^{–1} g ^{–1}	[71]
2018	SrTiO ₃ /SrCO ₃	NO	300 W Xe lamp, 420 nm	12 min	47%	[119]
2020	Bi/SrTiO ₃	NO	300 W Xe lamp, 420 nm	10 min	37%	[120]
2021	AZSTO	Tetracycline hydrochloride; Gram bacteria	350 W Xe lamp, λ ≥ 400 nm	60 min; 24 h	85%; 99,99%	[75]
2022	Ti ₆ Al ₄ V/TiO ₂ /SrTiO ₃	E. coli	UV lamp, 253.7 nm	24 h	3% (proliferation rate)	[124]
2019	Ga:PDA–SrTiO ₃	E. coli and S. aureus	in vivo	24 h	100%	[122]
2022	Cu _x O/Ag/SrTiO ₃	E. coli; toluene	visible light	24 h, 90 min	0.0989 min ^{–1}	[123]
2022	C-dots/Cu ₂ O/SrTiO ₃	E. coli; CTC·HCl	500 W Xe lamp >420 nm	60 min; 90 min	91,58%; 92,6%	[110]

saline solution with a pH of 7.0, and the detection limit reaches 2.1 and 1.9 nM for these preparations, respectively [73].

Energy storage

Energy can be stored in SrTiO₃ owing to its excellent dielectric properties. A recent study reported the construction of a nanocomposite based on SrTiO₃@SiO₂ plates in the form of a core-shell and polyvinylidene fluoride as a polymer matrix with excellent energy storage capacity. The design of the plates oriented along the direction of the electric field and the structural compatibility of the components are attributed to the improved values of E_b and U_e ($E_b = 402 \text{ MV m}^{-1}$, $U_e = 14.4 \text{ J cm}^{-3}$) compared with similar SrTiO₃-based nanocomposites in the form of nanoparticles (NP), nanofibres (NF), nanowires (NW), platelets (ST PS), ST@Al₂O₃ nanofibres (ST@Al₂O₃ NF), ST@PVP nanofibres (ST@PVP NF), and ST@PDA platelets (ST@PDA PS) [128–132,145].

In addition, effective MgFe₂O₄/SrTiO₃ and MgFe₂O₄/SiO₂ nanocomposites modified by the sol-gel method have been manufactured as anodes for lithium-ion batteries. The manufactured MgFe₂O₄/SrTiO₃ sample (crystallite size = 18 nm) exhibits an increased Coulomb efficiency of 64.1%. The results of electrochemical studies show that the MgFe₂O₄/SrTiO₃ sample has a high velocity index with a capacity of 330 mAh g⁻¹ and 65% retention in the second cycle, which is higher than that of MgFe₂O₄/SiO₂ (with a capacity of 252 mAh g⁻¹ and 42% retention in the second cycle) after recovering current densities to 100 mA g⁻¹ [133].

Biodiesel production

Nanocomposites based on SrTiO₃ can be used for biodiesel production owing to the catalytic reduction of acidic waste cooking oil. In a recent study [134], a heterogeneous SrTiO₃ catalyst doped with graphene oxide iron nanoparticles (IGO@SrTi) was used for producing fatty acid methyl esters (FAME) of biodiesel by reforming triglycerides and free fatty acids. The presence of SrTiO₃ nanoparticles in the composite facilitated the highly efficient production of FAME (96% within 180 min) owing to its potential properties such as high catalytic ability, chemical and thermal stability, and large surface area with abundant charge carriers.

Tables 2–4 list recent research results on the use of heterostructured photocatalysts based on SrTiO₃ nanoparticles in H₂ production, environmental remediation, and other electrochemical and dielectric applications, respectively. The effectiveness of composites in photocatalytic applications directly depends on the experimental conditions. These results confirm the considerable potential of composite SrTiO₃-based photocatalysts in photocatalytic, electrochemical, and dielectric applications. However, most of the results were obtained under laboratory conditions and require further study under more natural conditions for commercial and industrial purposes.

Nevertheless, autonomous prototypes have been developed for large-scale hydrogen production by the photocatalytic separation of water exposed to sunlight under natural conditions. In particular, photocatalytic panels with a total size of 100 m² have been developed using the composite SrTiO₃:Al, resulting in a solar-to-hydrogen (STH) efficiency of 0.76% and safe operation for several months under natural

Table 4 – The results of recent studies (2017–2022) on the use of SrTiO₃-based heterostructured photocatalysts nanoparticles in the electrochemical and dielectric applications.

Year	Photocatalyst	Application	Synthesis method	Efficiency	Ref.
2021	ST@SiO ₂ /PVDF	Energy storage	Solution casting	$D_{\max} \cdot D_{\text{rem}} = 9.14 \text{ } \mu\text{C cm}^{-2}$, $U_e = 14.4 \text{ J cm}^{-3}$ at $E_b = 402 \text{ MV m}^{-1}$	[145]
2021	SrTiO ₃ @PDA	Energy storage	Three-step molten salt	$D_{\max} \cdot D_{\text{rem}} = 8.65 \text{ } \mu\text{C cm}^{-2}$, $U_e = 12.45 \text{ J cm}^{-3}$ at $E_b = 350 \text{ MV m}^{-1}$	[128]
2019	ST@Al ₂ O ₃ NF/PVDF	Energy storage	Coaxial electrospinning	$U_e = 15.3 \text{ J cm}^{-3}$ at $E_b = 475 \text{ MV m}^{-1}$, $\eta = 68.5\%$	[129]
2018	STnws/P(VDF-CTFE)	Energy storage	Solution casting	$U_e = 8.8 \text{ J cm}^{-3}$ at $E_b = 3381 \text{ kV cm}^{-1}$, $\eta = 45\%$	[130]
2018	ST@PDA NFs	Energy storage	Solution casting	$U_e = 9.12 \text{ J cm}^{-3}$ at $E_b = 360 \text{ MV m}^{-1}$, $\eta = 61.1\%$	[131]
2017	ST NP/PVDF	Energy storage	Solution casting	$U_e = 5.1 \text{ J cm}^{-3}$ at $E_b = 2700 \text{ kV cm}^{-1}$, $\eta = 64.6\%$	[132]
2022	0.05%AC/TiO ₂ -25%SrTiO ₃	Photoanode for DSSC	Sol-gel	$\eta = 5.90\%$, $J_{\text{sc}} = 14.91 \text{ mA/cm}^2$, $V_{\text{oc}} = 714.71 \text{ V}$, FF = 55.46%	[126]
2019	SrTiO ₃ /TiO ₂	Photoanode for DSSC	Hydrothermal	$\eta = 2.68\%$, $J_{\text{sc}} = 7.01 \text{ (MA/cm}^2\text{)}$, $V_{\text{oc}} = 0.65 \text{ V}$, FF = 58%	[65]
2019	TiO ₂ : SrTiO ₃	Photoanode for QDSC	Doctor-blade	$\eta = 0.32\%$, $J_{\text{sc}} = 2.38 \text{ (MA/cm}^2\text{)}$, $V_{\text{oc}} = 0.37 \text{ V}$, FF = 31%	[127]
2019	SrTiO ₃ /N-GNS	Electrochemical sensor	Solothermal	0.038–100.0 μM for DPH and 0.030–90.0 μM for BRO	[73]
2022	MgFe ₂ O ₄ /SrTiO ₃	Li-ion battery anodes	Sol-gel auto combustion	1098 mAh g ⁻¹ at 100 mA g ⁻¹	[133]
2022	IGO@SrTiO ₃	Biodiesel production	Ultrasonication	96% FAME at 180 min	[134]

conditions [21]. However, despite the considerably low STH efficiency compared with that of a potential competitor such as a photovoltaic water electrolyser (30% STH), this photocatalytic reactor is in the initial stage of development and can serve as the basis for highly efficient prototypes for large-scale hydrogen production via photocatalytic water separation under natural solar radiation [14].

Conclusions and future prospects

Cubic perovskite SrTiO₃ is considered a promising material for photocatalytic applications because of its excellent physical and chemical characteristics such as high thermal stability, resistance to photocorrosion, high surface hydrophilicity, and a sufficiently stable structure to create heterogeneous composites. Moreover, SrTiO₃ has a higher electrical mobility at room temperature ($5\text{--}8\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$) than its potential competitor titanium dioxide (TiO₂) ($0.1\text{--}4\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$) in addition to a higher CB potential, which is favourable for photocatalytic applications. However, the wide bandgap, which narrows the spectrum of light absorption to the UV region, and the rapid recombination of photogenerated electrons and holes are the primary limitations of SrTiO₃. Based on the above-mentioned problems, we reviewed recent studies on the development of new heterogeneous SrTiO₃-based photocatalysts with reduced charge carrier recombination and operation in the visible radiation spectrum. Initially, we presented the primary methods for the synthesis of heterogeneous SrTiO₃-based photocatalysts with different morphologies and described the salient advantages and disadvantages of each method. However, considering these studies, highly effective SrTiO₃-based composites were obtained only in the laboratory, and further development is required with industrial and commercial technologies. Subsequently, we discussed various applications of modified SrTiO₃ particles that are obtained by alloying with metals and non-metals, creation of heterojunctions with highly conductive carbon modifications, deposition of co-catalysts, creation of oxygen vacancies, and modification of SrTiO₃ surfaces and their results were summarized. These strategies are aimed at improving the photocatalytic, electrochemical, and dielectric properties of SrTiO₃-based composites, which are expected to have wide practical applications. Numerous studies clearly indicate that the limiting factors of thermally and chemically stable SrTiO₃ can be modified because of the adjustable bandgap width, and the creation of a heterojunction increases the lifetime of photogenerated charge carriers, which makes this material more promising than its competitors for future applications. Although the synthesised SrTiO₃-based composites yielded highly effective results in a laboratory environment, they can be considerably different under natural conditions. Thus, further efforts should be directed towards developing modified SrTiO₃-based photocatalysts that function effectively over a wide UV–visible radiation spectrum *in vivo* for large-scale applications. As described previously, owing to their photocatalytic, electrochemical, and dielectric properties, SrTiO₃-based composites have broad prospects for practical applications to address environmental pollution, energy shortage, and storage of the generated energy. Therefore, to

improve the efficiency of large-scale operations, the key strategies for development over the next decade should focus on.

- (1) Enhanced performance and efficiency. It is anticipated that significant advancements will be made in optimizing the performance of SrTiO₃-based composites. This could involve improving their photocatalytic efficiency, stability, and selectivity. Strategies such as novel synthesis techniques, bandgap engineering, and surface modification may be explored to achieve superior performance.
- (2) Tailored properties for specific applications. Future developments will focus on tailoring the properties of SrTiO₃-based composites to meet specific application requirements. This may involve precise control over composition, structure, morphology, and surface properties. By customizing these parameters, researchers can optimize the photocatalytic activity and selectivity of SrTiO₃-based composites for targeted environmental and energy applications.
- (3) Integration with emerging technologies. Over the next decade, there may be an increasing focus on integrating SrTiO₃-based composites with other technologies to enhance their functionality and applicability. For instance, coupling with energy storage systems, catalysts, or electrochemical devices could enable more efficient utilization of the generated energy or facilitate multi-step reactions for complex photocatalytic transformations.
- (4) Sustainable and scalable production methods. As the demand for efficient and environmentally friendly materials grows, the development of sustainable and scalable production methods for SrTiO₃-based composites will be crucial. This may involve the exploration of green synthesis approaches, utilization of renewable resources, and efficient recycling strategies to ensure the eco-friendly production and utilization of SrTiO₃-based composites on a larger scale.

We expect that this review will provide new insights for future research on synthesis technologies and consequently improve the various applications of modified SrTiO₃-based photocatalysts to solve modern problems related to the environment, health, and energy.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zh. Kusanov A. Umirzakov A. Serik A. Baimenov M. Yeleuov Ch. Daulbayev.

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