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Review

Reviewing Perovskite Oxide-Based Materials for the Effective Treatment of Antibiotic-Polluted Environments: Challenges, Trends, and New Insights

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Abstract: Society confronts the pressing environmental challenges posed by the pervasive presence of toxic pollutants in aquatic ecosystems. The repercussions of contaminant release extend far and wide, endangering marine life and human well-being. While various techniques such as bioremediation, filtration, and adsorption have been employed for wastewater treatment, they grapple with cost effectiveness and overall efficiency issues. Advanced oxidative processes, including photocatalysis and Fenton, have emerged as viable solutions in response to the emerging contaminants. However, the efficacy of photocatalysis largely hinges on the choice of catalyst. Their distinctive attributes, such as chemical defects and exceptional stability, make perovskite oxides a promising catalyst. These materials can be synthesized through diverse methods, rendering them versatile and adaptable for widespread applications. Ongoing research endeavors are diligently focused on enhancing the performance of perovskite oxides, optimizing their integration into catalytic processes, and exploring innovative approaches for material immobilization. This comprehensive review seeks to elucidate the most pivotal advances in perovskite oxides and their composites within the wastewater treatment domain. Additionally, it sheds light on burgeoning research trends and multifaceted challenges confronting this field, which present insights into techniques for treating the antibiotic-contaminated environment, delving into innovative strategies, green technologies, challenges, and emerging trends.

Keywords: environmental remediation; emerging pollutants; advanced materials; perovskites; metal oxides

1. Introduction

Contemporary society faces various environmental challenges related to toxic pollutants and their dissemination in the environment [1,2]. Aquatic ecosystems play a crucial role in sustaining life on the planet and represent the primary destination for various contaminants. Furthermore, the availability of potable water is declining, primarily due to human activities [3]. The rapid advancement of agriculture and industry has significantly contributed to the release of pollutants into aquatic systems, posing threats to marine life and human health [4]. Projections indicate that by 2030, the planet could face a global water deficit of around 40%, driven by the degradation of the quality and quantity of water resources [5]. Discharge of industrial effluents and urban wastewater has also exacerbated water pollution, emphasizing reusing these waters as a viable alternative [1,6].

Simultaneously, antibiotics in the environment have become a growing concern due to potential impacts on human health and aquatic ecosystems [7]. Antibiotics are used widely in human medicine, veterinary medicine, and agriculture. However, a portion of these compounds is excreted by treated organisms, entering water bodies through hospital effluents, domestic sewage, and agricultural waste [8,9]. Furthermore, pharmaceutical production and improper disposal contribute to environmental contamination. The presence of antibiotics in the environment can have highly adverse consequences, such as the development and dissemination of bacterial resistance [10], reducing the effectiveness of antibiotics in treating infections [4,11]. Besides the financial costs, antibiotics pose a significant risk to humans and other organisms in the environment [12].

Given these concerns, it is essential to develop remediation strategies to minimize the presence of antibiotics in the environment and ensure water quality [13]. Several techniques are available for treating antibiotic contamination in water, including physical, chemical, and biological processes [14–18]. The variety of techniques allows adaptation to the specific conditions of each case, selecting the most effective and cost-effective method considering the available infrastructure. Additionally, the search for more effective water treatment methods has been a central goal for experts in the field [19]. Advanced oxidative processes, such as photocatalysis and the Fenton process, have emerged as practical solutions to mitigate the impacts of human activities on water [20].

In this context, perovskite oxides have emerged as promising candidates for treating contaminated waters, offering advantages such as the presence of chemical defects and thermal and chemical stability [21]. Perovskite oxides have the general formula ABO_3, where A represents alkaline earth metals and B represents transition metals [22]. The cubic structure, which can be distorted to orthorhombic and tetragonal, allows the incorporation of metallic ions [21,23]. Figure 1 illustrates which chemical elements of the periodic system may be used to create various perovskites. Based on the number of elements available, producing more than 15 million unique variations of perovskites, each with specific properties, is possible [24]. Current research focuses on improving perovskite oxides's performance and optimizing their use in catalytic processes [25]. Therefore, this review aims to present and analyze the most relevant advances related to perovskite oxides and their composites in treating contaminated waters, addressing research trends and challenges in this field.

This review not only discusses the challenges related to the presence of antibiotics in water and wastewater treatment technologies but also explores the potential of perovskites as innovative heterogeneous catalysts for the efficient degradation of antibiotics and other pollutants in contaminated waters. Combining environmental concerns regarding emerging pollutants in water with perovskite-based materials offers a promising approach to addressing these challenges more effectively and sustainably.

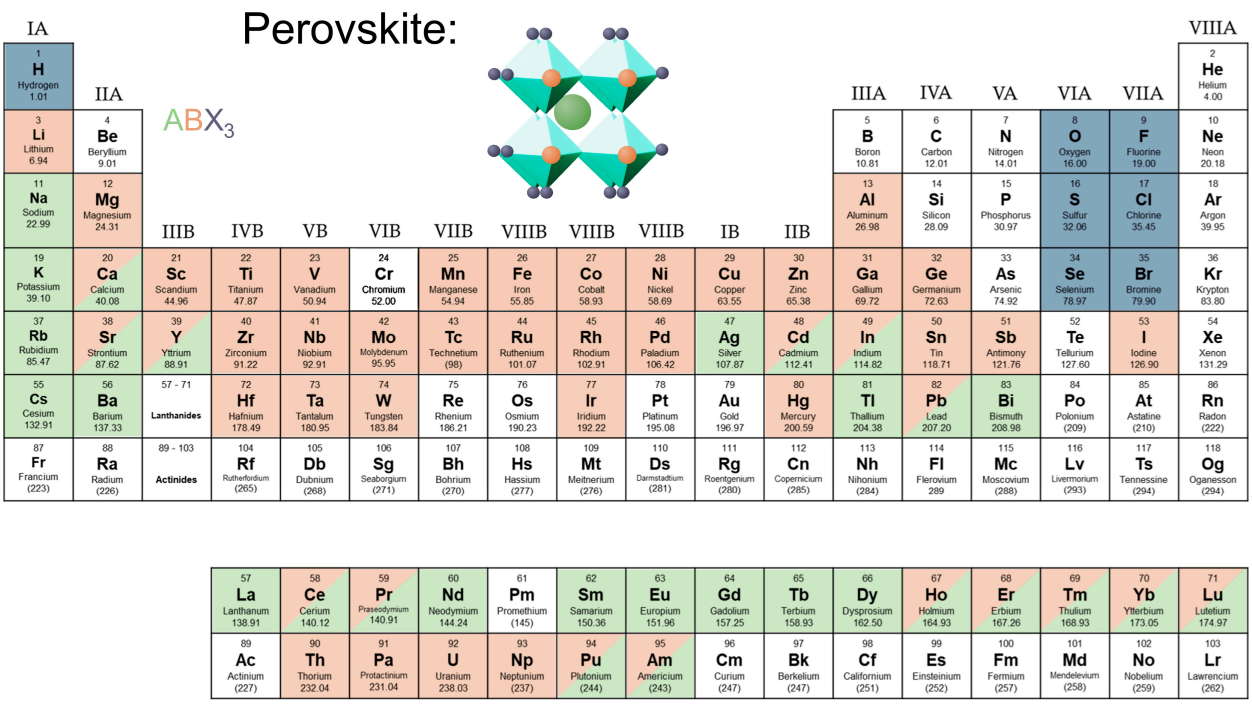

Figure 1. Chemical elements of the periodic table used in the production of perovskites.

2. Antibiotic Classes and Negative Effects on the Environment

Antibiotics are crucial in combating bacterial infections and are categorized based on their mechanisms and specificities [26]. Penicillin and cephalosporins are effective against Gram-positive and some Gram-negative bacteria, while macrolides treat respiratory and soft tissue infections [27]. With a broad spectrum of action, tetracyclines are effective against various bacteria but pose risks like photosensitivity and bacterial resistance [26]. Quinolones, such as ciprofloxacin, are potent but restricted due to safety concerns, while sulfonamides and glycopeptides are used for specific infections [28]. The indiscriminate use and inadequate disposal of antibiotics contribute to environmental pollution, fostering bacterial resistance and posing a significant global health challenge [7]. In addition, antibiotic residues disrupt ecosystems, impacting wildlife health and facilitating the horizontal transfer of resistance genes [11]. The environmental impact extends to non-target organisms [11], affecting aquatic life [29] and soil health, necessitating responsible antibiotic use and effective disposal strategies to minimize these consequences [30]. Figure 2 shows possible transformation and migration pathways for the antibiotics in the water environment and soil. Thus, it is vital to adopt responsible antibiotic use practices in both human and veterinary medicine. In this sense, effective disposal strategies, such as the appropriate treatment of effluents and improving techniques for remediating antibiotics in the ecosystem, are essential to minimize the environmental impact. Therefore, the following topic addresses and discusses the leading technologies for remediating antibiotics in the environment.

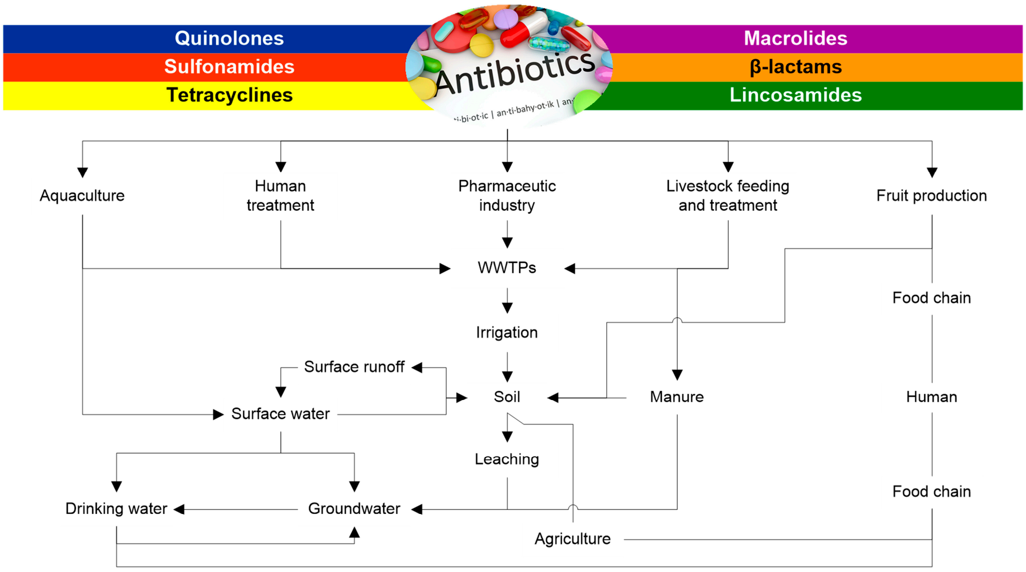

Figure 2. Possible transformation and migration pathways for the antibiotics in the water environment and soil.

3. Antibiotics Remediation Technologies

Antibiotic remediation technologies are crucial in reducing contamination and protecting the environment and public health [31]. Technologies that include a variety of physical, chemical, and biological approaches aimed at degrading, removing, or inactivating the antibiotics present in the analyzed matrix. Figure 3 illustrates the number of publications in recent years related to the keyword "Antibiotic Remediation" (Scopus). It can be observed that the interest of the scientific class in the subject has increased every year. From 2021 to 2023, the number of publications corresponds to more than 60%, with China and India being the main areas with published documents.

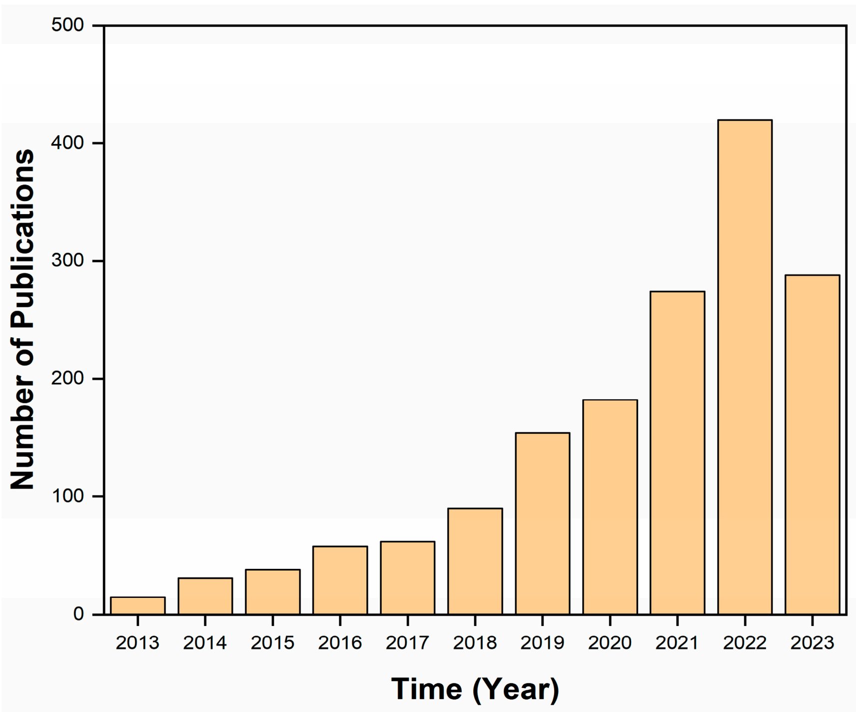

Figure 3. Number of publications in recent years related to the keyword "Antibiotic Remediation" (Scopus).

Figure 4 illustrates a map with the main words in publications that addressed the theme. The VOSViewer software version 1.6.19 was used for bibliometric analysis [32]. The main keywords on the map were adsorption, photocatalysis, separation, plants, adsorbent, biochar, composite, and catalyst. Also, ciprofloxacin, tetracycline, and sulfamethoxazole were the three antibiotics that most appeared in the analyzed documents.

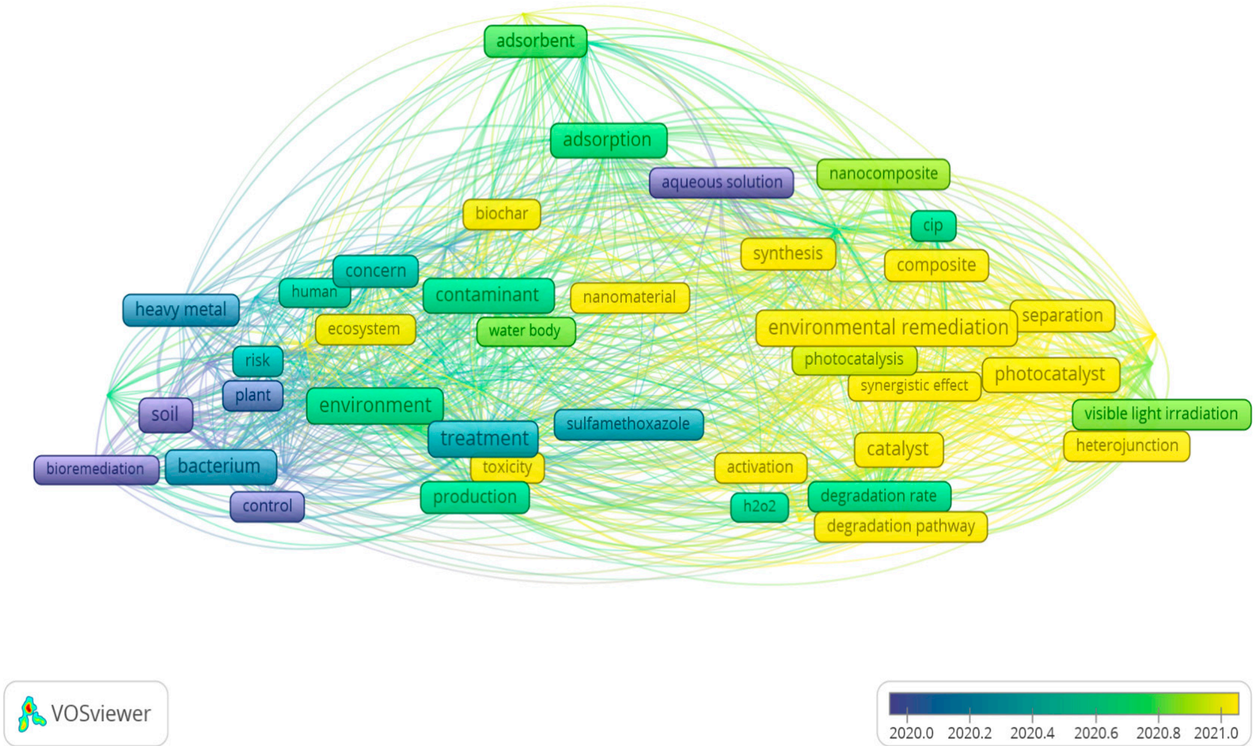

Figure 4. Map with the main words in publications that addressed the theme from 2013 to 2023.

Figure 5 shows a schematic diagram of the various processes used to treat wastewater contaminated with antibiotics and other emerging pollutants. Physical remediation technologies involve several techniques, such as, adsorption and membrane separation [14]. Chemical technologies use chemical reactions to degrade antibiotics or convert them to less toxic compounds, for example, ozonation and photocatalysis [33]. Biological processes applied in the remediation of antibiotics involve the use of microorganisms, such as bacteria and fungi, which may metabolize and degrade pollutants [28]. It is important to emphasize that antibiotic remediation technologies must be adapted to the specific characteristics of each contamination scenario, considering factors such as antibiotic concentration, environmental conditions, and technical and economic feasibility [34]. Furthermore, continuous research and development of new technologies are needed to improve the efficiency and sustainability of treatment processes. In this topic, the leading antibiotic remediation technologies, highlighting the process performance, limitations, and recent scientific advances in the area, providing a comprehensive view on the subject, and demonstrating the potential of technologies to mitigate contamination by antibiotics in water, were explored.

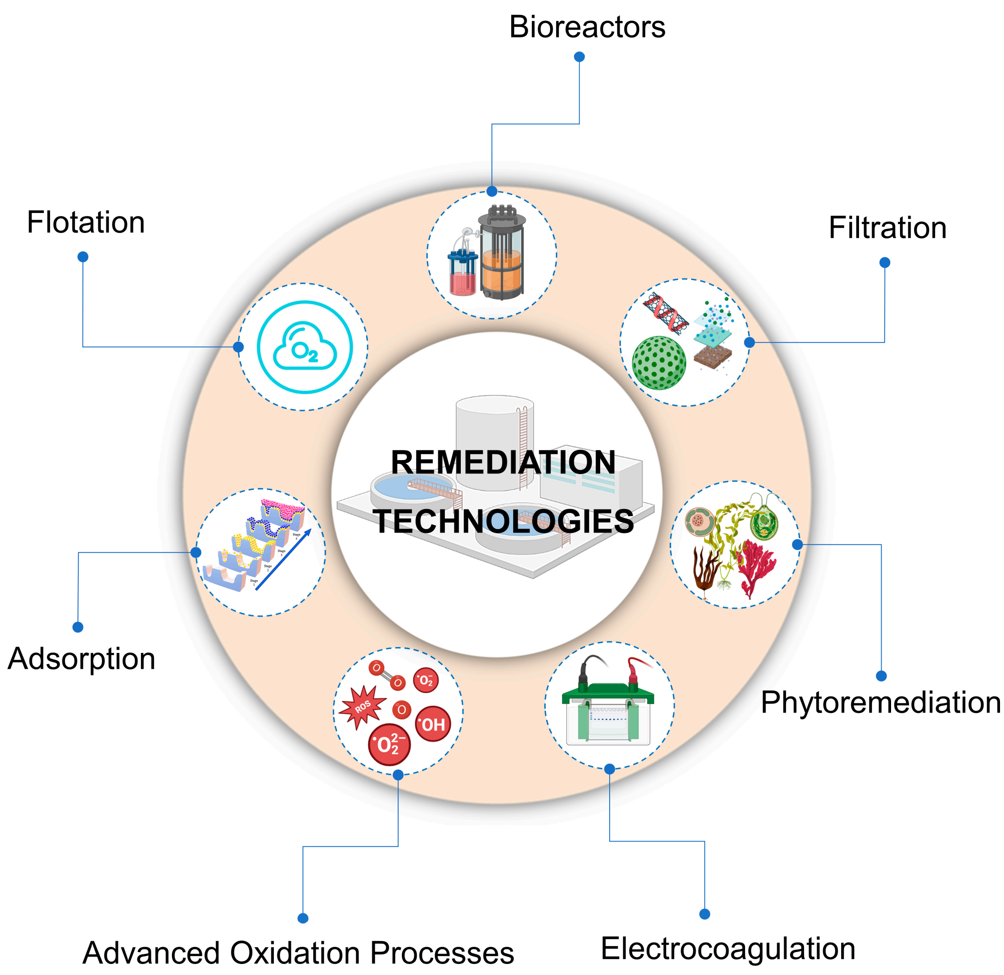

Figure 5. A schematic of the various processes used to treat wastewater contaminated with antibiotics and other emerging pollutants.

3.1. Physical Techniques

There are several physical techniques used to remove antibiotics from contaminated water [15]. The methods aim at the physical separation of antibiotic compounds from the aqueous medium and allow the recovery of treated water with lower concentration or without the contaminant. The main physical techniques reported are filtration, adsorption, sedimentation, flotation, and membranes. Filtration is commonly used to remove solid particles and dissolved substances from water [35]. The process can be performed by filters made of different materials, such as sand. In addition, filtration can be carried out in several stages, applying filters with different porosity to remove other particles of various sizes [36]. Therefore, filtering membranes are used in techniques such as microfiltration, ultrafiltration, and reverse osmosis. Membranes usually have controlled size pores that allow water to pass through but retain larger particles and compounds, including antibiotics [37]. The application of pressure or vacuum can enhance the water flow through the membranes and remove unwanted compounds.

Treatment of water contaminated with several classes of tetracyclines applying the coagulation and filtration process with granular activated carbon has been reported [15]. Both approaches were suitable for antibiotic removal depending on the type of antibiotic studied. However, filtration with granular activated carbon was relatively more effective with tetracycline, doxycycline hyclate, and chlortetracycline hydrochloride compared to coagulation treatment, which presented greater difficulty in removing these compounds. A filtration matrix made of a new composite based on macroporous metal-polyphenol and melamine foam was tested for tetracycline removal [16]. The matrix removed virtually

100% of the pollutant in wastewater within 30 min. In addition, the filtration membrane showed an excellent ability to reuse and remove tetracycline in milk and dairy manure wastewater through a dynamic adsorption system.

Adsorption is a process in which compounds present in water adhere to the surface of a material called adsorbent [9]. Materials such as activated carbon, zeolites, and ion exchange resins are often used to adsorb antibiotics in water [38]. Adsorption is quite effective in removing organic compounds and can be combined with other techniques to improve treatment efficiency. Biochars produced from three raw materials (biosolids, cattle manure, and spent coffee grounds) were applied in low or high concentrations to remove seven antibiotics [14]. All biochars used, even at low concentrations, efficiently removed more than 70%. Biochars applied at a high dose showed an excellent rate of rapid (5 min) and complete removal of tetracycline, erythromycin, and clarithromycin. However, the application of biochar to remove ofloxacin and sulfamethoxazole was ineffective. Nanostructured biochar produced from pomegranate peels showed promising potential for ciprofloxacin removal [39]. The adsorption capacity of the nanostructured was about 26.85 times higher than bulk pomegranate peels. Furthermore, the study for ciprofloxacin removal from real effluents using batch reactor and fixed bed was 89.94% and 84.74%, respectively.

Sedimentation is a gravity-based process that effectively separates solid particles and dissolved compounds from water. It is widely used in wastewater treatment plants where contaminated effluent can settle, allowing the particles and compounds to naturally separate and accumulate within the tank. Finally, the clarified water can be easily separated from the top. The combined process of polyferric sulfate coagulation, Fenton, and sedimentation was applied to treat non-degradable antibiotic fermentation wastewater [40]. The sedimentation process was crucial for removing pollutants right after treatment with the Fenton process at neutral pH. Overall color removal, chemical oxygen demand, and suspended solids reached 97.3%, 96.9%, and 86.7%, respectively. Therefore, applying combined processes may be a suitable way to treat wastewater from different fields, for example, the pharmaceutical industry. The application of the flocculation process may be an interesting strategy for the removal of antibiotics from water. However, most conventional flocculants are not effective. Therefore, scientific efforts have been applied to produce new flocculants. Fabrication of a flocculant based on a thermosensitive and cationic organic polymer was employed to remove antibiotics. The removal of levofloxacin and tetracycline using the developed flocculant was 68.71% and 66.83%, respectively [41].

Flotation is a technique in which microbubbles of air or other gas are applied to the water so that adsorbed particles or compounds attach to the bubbles and float to the surface where they can be separated. Flotation is particularly efficient at removing organic compounds, e.g., antibiotics. The application of a new system consisting of modified dissolved air flotation and self-excited oscillating pulsed cavitation-impinging processes was tested for removing antibiotics, microplastics, and antibiotic resistance genes [2,42]. The treatment application with only self-excited oscillating pulsed cavitation impinging promoted the removal of more than 97% and 100% of antibiotics and antibiotic resistance genes, respectively. The combined system removed virtually all antibiotics, 99.2%. Some physical techniques commonly used to remove antibiotics from water have been discussed in this topic. It is important to emphasize that the appropriate approach depends on the specific characteristics of the contaminated water, the concentrations of antibiotics, and the required performance. Furthermore, the combination of different physical techniques has been adopted to maximize the efficiency of the removal process.

3.2. Chemical Techniques

Several chemical techniques may be used to remove antibiotics from water [34,43]. The methods involve chemical reactions that aim at the degradation, transformation, or removal of compounds present in the aqueous matrix. The main chemical techniques used to treat wastewater containing antibiotics are advanced oxidative processes, chlorination, and chemical precipitation [43]. Advanced oxidation techniques involve the application of strong oxidants, for example, hydrogen peroxide, ozone, or potassium persulfate, to oxidize and degrade the compounds [44,45]. The presence of oxidants leads to the production of highly reactive free radicals, which attack and break the chemical bonds of pollutants, transforming them into less toxic or completely inactive products. However, the ideal form of an advanced oxidative process is the conversion of pollutants into water and carbon dioxide [22].

Additionally, chemical reduction processes can reduce some antibiotics to be less toxic. The addition of reducing agents, such as sodium bisulfite and zero-valent iron, may reduce inactive or less harmful forms of antibiotics from reacting with pollutants [46]. The presence of two oxidants, hydrogen peroxide, and peroxydisulfate, in a photocatalytic treatment based on metal–organic structures using Basolite F300 was investigated in the degradation of lincomycin [17]. The presence of both oxidants demonstrated that the process was highly effective, with potentiation possibly occurring through heterogeneous Fenton-type reactions. The use of a zeolitic iron molybdate-based octahedral metal oxide for the degradation of ciprofloxacin together with hydrogen peroxide was reported [47]. Treatment with metal oxide and hydrogen peroxide resulted in the removal of the antibiotic in neutral and weakly alkaline water matrices (78%; 5 h).

Chlorination is a process in which chlorine is added to water for disinfection and removal of contaminants [48]. Chlorine reacts with compounds in the water, oxidizing them and inactivating antimicrobial activity. However, chlorination may form highly undesirable by-products, such as trihalomethanes, which may pose risks to human health. A study investigated the chlorine degradation of two typical macrolide antibiotics, erythromycin and roxithromycin, and identified the transformation products formed [49]. The chlorinated by-products of erythromycin and the reduced hydroxylation products of roxithromycin exhibited greater ecotoxicity than the respective parent compounds. However, algal growth inhibition assays showed that the overall ecotoxicity of the chlorinated mixture of erythromycin or roxithromycin was lower than that of the antibiotics before chlorination. The chlorination process must be thoroughly evaluated before being implemented in real wastewater treatment plants, as harmful substances may be formed for the ecosystem.

Heterogeneous photocatalysis is a widely applied process that uses light energy to trigger chemical reactions [26]. In heterogeneous photocatalysis, a catalyst such as titanium dioxide is added to water contaminated with antibiotics. Once the catalyst is activated by light, reactive oxygen species are generated to oxidize and degrade the substances. Hafnium oxide nanohybrids with separate incorporation of ruthenium and platinum nanoparticles were applied in the photocatalytic treatment of nitrofurantoin and ciprofloxacin [50]. Both nanohybrids showed complete removal of the two antibiotics in a short time.

Furthermore, the degradation achieved in the photocatalytic process was predominantly governed by hydroxyl radicals through oxidation. The preparation of carbon nitride modified by nitrogen vacancies and oxygen replacement was applied in the degradation of tetracycline, ciprofloxacin, and sulfadiazine under visible light irradiation [51]. The modified carbon nitride showed the degradation activity of all studied antibiotics compared to the unmodified material, demonstrating great potential for application in real conditions.

Perovskite $LaNiO_3$ co-substituted by Ce and Cu elements with enhanced photocatalytic performance for the degradation of the norfloxacin was reported [52]. The photodegradation capacity and the TOC removal efficiency were almost two times higher than that of pure $LaNiO_3$. As per the authors, incorporating Ce and Cu as partial substitutes for La and Ni in perovskite materials proves to be a straightforward method for enhancing the photocatalytic performance in water treatment, particularly in the degradation of antibiotics. Figure 6 shows a hypothetical mechanism diagram of $La_{0.9}Ce_{0.1}Ni_{0.9}Cu_{0.1}O_3$ proposed in the reported work.

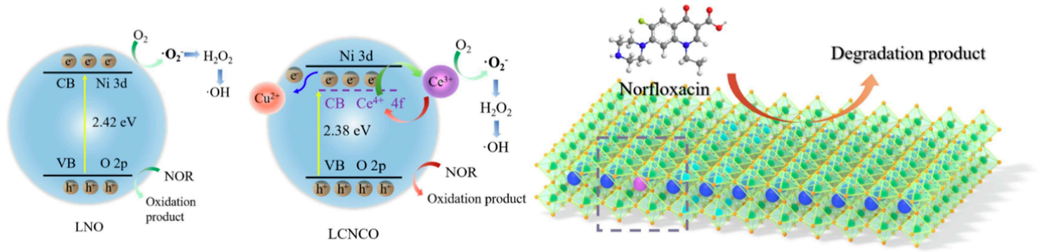

Figure 6. A hypothetical mechanism diagram of $La_{0.9}Ce_{0.1}Ni_{0.9}Cu_{0.1}O_3$. Reproduced with permission from [52].

A novel catalyst composed by ultrathin aurivillius perovskite $Bi_4Ti_3O_{12}$ nanosheets and typical perovskite $LaCoO_3$ particles was developed [53]. The authors assert that this novel composite catalyst has demonstrated remarkable catalytic activity and impressive stability in the degradation of tetracycline, achieving an efficiency of 87.8%. Furthermore, even after undergoing four cycles, the catalyst'ss activity remained considerable at 78.4%. Table 1 shows other reported works that applied perovskite oxides in the degradation of antibiotics.

Table 1. Some reported work on the application of perovskite oxide for antibiotic degradation via the photocatalytic process.

Technique	Process	Material	Drug	Ref.
Chemical	Photocatalytic	$La_{0.9}Ce_{0.1}Ni_{0.9}Cu_{0.1}O_3$	Norfloxacin	[52]
		$LaCoO_3$ and $Bi_4Ti_3O_{12}$	Tetracycline	[53]
		$LaZnO_3$	Sulfamethizole	[54]
		$CeMnO_3$	Tetracycline hydrochloride	[55]
		$CaFe_2O_4$ and $LaFeO_3$	Tetracycline	[56]

Chemical precipitation involves adding specific chemicals to contaminated water to form insoluble compounds. Insoluble compounds may include complexes with antibiotics, which precipitate and can be removed by sedimentation or filtration. Chemical precipitation is often combined with other treatments to increase removal efficiency. The application of portlandite aqueous carbonation in removing amoxicillin, ceftriaxone, and cefazoline was recently reported [57]. The treatment showed the best removal rate for amoxicillin, followed by cefazoline and ceftriaxone. Another study prepared a series of two-dimensional catalysts (LFCO/Ti_3C_{2-x}) by dispersing perovskite on layered Ti_3C_2 for a microwave-combined peroxymonosulfate-catalyzed degradation of ciprofloxacin [58]. Figure 7 shows a probable mechanism of antibiotic degradation using the material reported in the study with LFCO/Ti_3C_{2-x}. Under the optimal treatment conditions, the catalyst achieved 96.49% removal efficiency within 14 min. Also, another promising approach is the catalytic oxidation of antibiotics utilizing hybrids composed of perovskite oxide-based materials and biological enzymes. Perovskite oxides, known for their unique structural and catalytic properties, are integrated with biological enzymes to create synergistic hybrid systems capable of efficiently degrading antibiotics. This interdisciplinary strategy harnesses the catalytic prowess of perovskite oxide materials and the specificity of biological enzymes, enhancing the overall efficacy of antibiotic oxidation processes. This novel avenue holds great potential for addressing antibiotic pollution, offering a sustainable and tailored solution to mitigate the environmental impact of these pharmaceutical compounds. To date, few studies have explored this approach [59–61]. Exploring such hybrid systems contributes to advancing our understanding of catalytic oxidation mechanisms. It paves the way for the development of environmentally friendly technologies in the realm of wastewater treatment and antibiotic remediation. Finally, it is essential to consider that the appropriate chemical technique depends on the properties of the antibiotics present in the water, the environmental conditions, and the quality of the treated water which should be achieved by ecological regulations. It is also important to evaluate and control the possible by-products or residues generated by chemical processes to ensure the safety and sustainability of treatment of wastewater contaminated with pharmaceuticals.

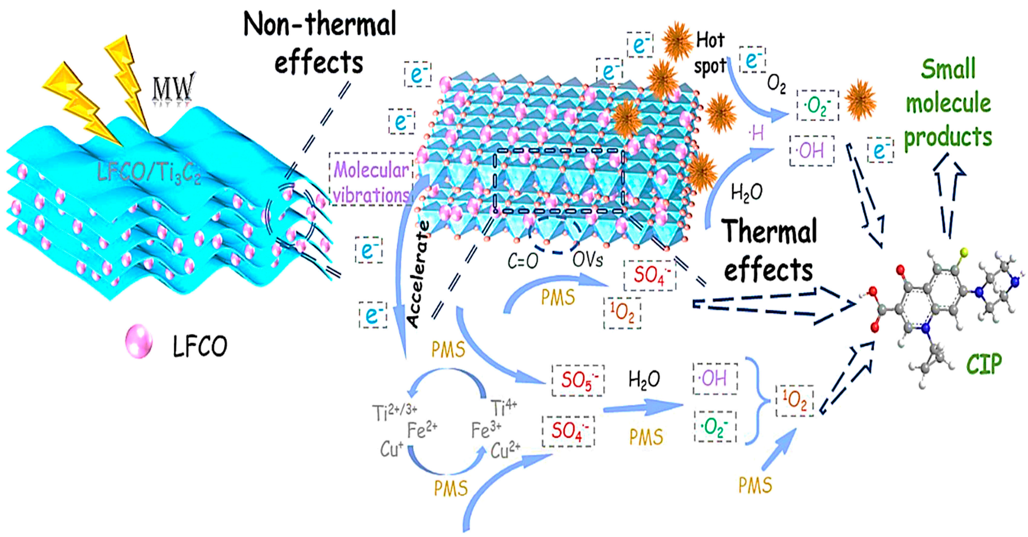

Figure 7. Possible degradation pathways of CIP using LFCO/$Ti_3C_{2\text{-}0.1}$. Reproduced with permission from [58].

3.3. Biological Techniques

Biological techniques have been widely used to remove antibiotics from contaminated water, mainly taking advantage of the ability of microorganisms to degrade and metabolize the compounds [62]. Some of the main biological techniques employed are bioremediation, phytoremediation, and biofiltration [63]. Bioremediation is a process that uses microorganisms, such as bacteria, fungi, and microalgae to degrade the antibiotics in water. Microorganisms have enzymes capable of breaking the chemical bonds of antibiotics and converting them into products with less or no toxicity [63]. Bioremediation can be carried out in biological reactors or treatment ponds, where microorganisms can be cultivated and maintained under suitable conditions to optimize the degradation of antibiotics. The activated sludge process is another biological technique widely used in wastewater treatment [62], including effluents contaminated with antibiotics. In this process, microorganisms are mixed with contaminated water in an aerobic reactor, where they feed on the organic compounds present and degrade them through metabolic processes, eventually leading to the separation of the sludge from the treated water, which removes the pollutants [64].

Removal of oxytetracycline through a bioremediation system has recently been reported [65]. The bioremediation system contained an organism isolated from oxytetracycline-enriched activated sludge, *Achromobacter* sp., which showed the ability to remove the studied antibiotic via co-metabolic biotransformation. The microorganism was isolated in alginate, and the developed system showed significant removal of more than 60% of the pollutant with a hydraulic retention time of 10 h. Bioremediation mediated by microalgae and a microalgae–bacteria consortium for ciprofloxacin treatment was also evaluated [63]. The maximum ciprofloxacin removal efficiencies by the pure microalgae and the consortium were 87.5% and 96.1%, respectively. The presence of symbiotic bacteria in the consortium improved ciprofloxacin biodegradation by reducing microalgae cell damage and accelerated the rate of antibiotic elimination by secreting fulvic acid-like compounds. Also, nitrogen-fixing bacteria in the microalgae–bacteria consortium suggested that improved biodegradation may be associated with nitrogen co-metabolism.

Phytoremediation involves using plants to remove compounds from a polluted system, such as water contaminated with antibiotics [66,67]. Some plant species may absorb and metabolize drugs through root systems. The acting plants act as "living filters", where the plants capture and degrade antibiotics [68]. Phytoremediation may be used in systems such as built-up wetlands or agricultural areas to treat water contaminated with antibiotics. Phytoremediation may generally be categorized into phytoextraction, phytostabilization, phytovolatilization, phytofiltration, and phytotransformation [68]. Figure 8 illustrates a scheme with the main types of reported phytoremediation.

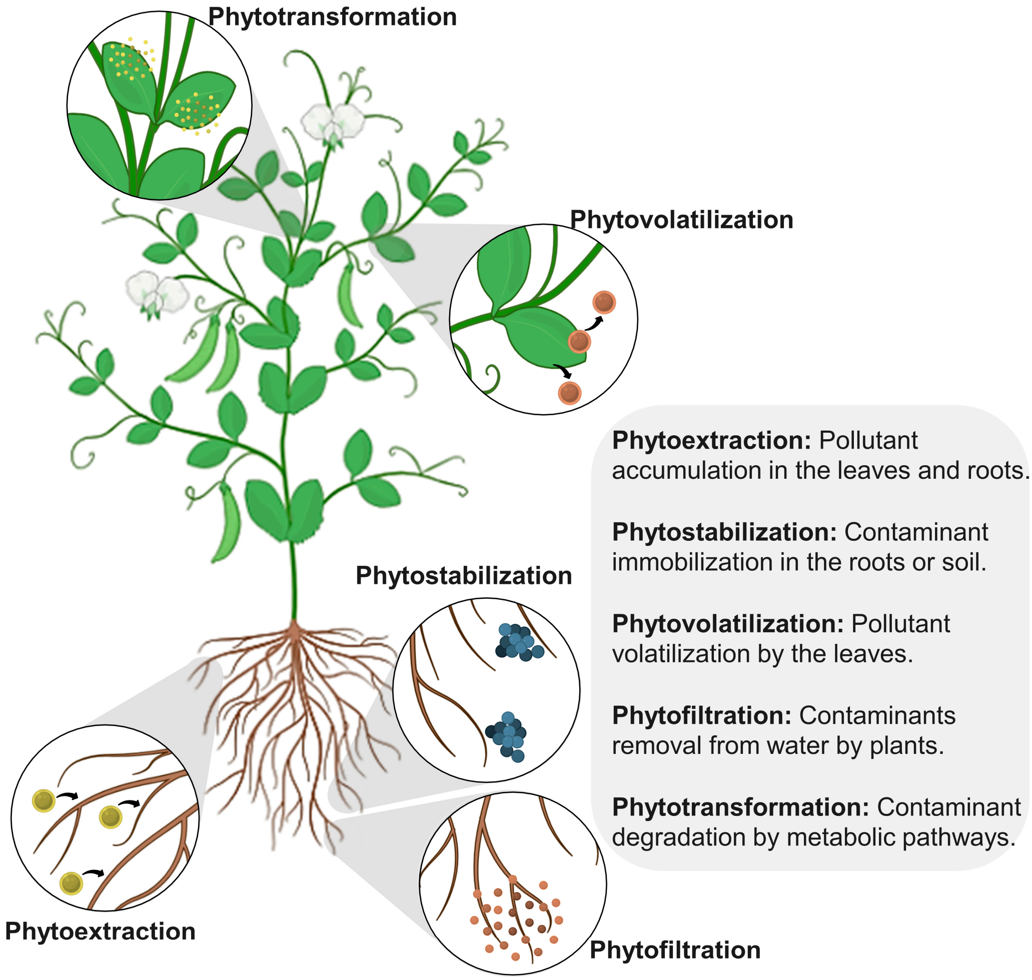

Figure 8. Scheme with the main types of reported phytoremediation.

Substrate-free hydroponic microcosms of *Myriophyllum aquaticum* were used to evaluate the phytoremediation potential of water contaminated with antibiotics and copper [28]. Efficient antibiotic removal was achieved by the hydroponic microcosm of 88–99%, 83–99%, and 99% for tetracycline, oxytetracycline, and chlortetracycline, respectively. The uptake and metabolism of clarithromycin and sulfadiazine in lettuce under controlled hydroponic conditions were also reported [69]. Concentrations of clarithromycin and sulfadiazine reached 1629 $g \cdot kg^{-1}$ and 683 $g \cdot kg^{-1}$ in lettuce leaves, respectively, and 4977 $g \cdot kg^{-1}$ and 24,599 $g \cdot kg^{-1}$ in lettuce roots, respectively. Phytoremediation has been used widely for removing pollutants from soil and water, offering significant environmental benefits. However, it is vital to consider some potential hazards associated with phytoremediation, particularly concerning human exposure. The main hazards reported may be related to the accumulation of pollutants in plants and the release of toxic by-products into the environment.

Biofiltration is another biological technique that uses a biologically active filter medium to remove pollutants from the water that must be treated. The filter medium is colonized by microorganisms capable of degrading antibiotic compounds [35]. Contaminated water passes through the filter medium, in which the microorganisms adhered to the medium carry out the degradation of the pollutants. Biofiltration is considered efficient in removing organic compounds and has been successfully applied in the treatment of water contaminated with antibiotics [70]. Furthermore, biological oxidation is another process that combines microorganisms and chemical oxidation to degrade antibiotics. Microorganisms are used to metabolize antibiotics, while complementary chemical reactions contribute to the degradation of the compounds [65]. Biological oxidation is an approach that combines the benefits of biological and chemical techniques, improving the efficiency of antibiotic removal in the aqueous medium. Biological techniques offer numerous advantages, such as the use of natural processes, the reduction of unwanted by-products, and the efficiency of removing antibiotics from contaminated water [71]. However, the need for proper control of operating conditions and careful selection of microorganisms and plants to ensure the efficiency and safety of the remediation process is critical to achieve satisfactory process performance. In general, the excellent choice of technique for the type of effluent to be treated and the conditions needed to reach the concentration of the pollutant are vital for the success of the treatment. Table 2 shows the performance comparison of several techniques reported for treating drug-contaminated systems. Thus, studying the treatment and knowing about the risks it also poses to the ecosystem, for example, the generation of by-products more toxic than the original, becomes a prerequisite for implementing any remediation process.

Table 2. Performance of different techniques applied in the drugs removal.

Technique	Process	Drug	Removal	Ref.
Physical	Adsorption	Tetracycline	99%	[72]
	Adsorption	Ciprofloxacin	100%	[73]
	Filtration and adsorption	Tetracycline	>90%	[35]
Chemical	Electron beam	Sulfathiazole	90%	[74]
	Photocatalysis (Visible light)	Amoxicillin, azithromycin, cefixime, and ciprofloxacin	99.99%, 99.99%, 99.89%, and 99.98%	[33]
	Catalysis	Trimethoprim	100%	[44]
Biological	Enzyme-based	Diclofenac	92%	[75]
	Hybrid bioreactor	Several	>90%	[37]
	Enzyme-based	Carbamazepine	95%	[76]

While antibiotic remediation technologies are pivotal in addressing antibiotic contamination in water, pursuing more effective and sustainable methods remains a top priority. The escalating use of antibiotics in various sectors, including human medicine, veterinary medicine, and agriculture, has heightened their presence in our aquatic ecosystems, giving rise to concerns regarding their impacts on human health [30,77]. Despite observing remarkable advances in water treatment techniques, many of these approaches encounter significant challenges, such as prohibitive costs and adverse environmental repercussions. Consequently, the scientific community has increasingly focused on discovering more efficient and sustainable strategies to grapple with this intricate issue.

In this context, the application of perovskite-based materials has emerged as a promising prospect [24,78]. As we delve into the intricacies of antibiotic remediation, we shift our attention toward the transformative potential offered by these materials. Perovskites are renowned for their distinctive crystal structure and catalytic properties, rendering them ideal candidates for purifying water contaminated with emerging pollutants [79]. The crystalline structure allows for the incorporation of metal ions and the presence of chemical defects, enhancing their catalytic prowess. Moreover, perovskites exhibit robust thermal and chemical stability, rendering them highly appealing for deployment in demanding water treatment environments [80]. By exploring this topic, we will present how perovskites promise to revolutionize the treatment of antibiotic-contaminated water and other emerging pollutants, highlighting a new era of unparalleled efficiency and sustainability.

4. Perovskite Oxide-Type Materials: Synthesis Strategies and Characteristics

The production of perovskite oxide-type materials has increased significantly in recent years for various applications [21]. Gustav Rose first discovered the mineralogical structure known as perovskite, with the chemical formula $CaTiO_3$, in the Ural Mountains in Russia in 1839 [81]. There are numerous variations of perovskites in the Earth'ss crust, for example, $MgSiO_3$ [82]. Since its discovery, many studies have been carried out to explore possible applications for perovskite [83]. Synthetic compounds that follow the general formula ABX_3 have structures like $CaTiO_3$ and are, therefore, also called perovskites (Figure 9) [84]. In the cubic structure of perovskite oxide (ABO_3), the B cation is at the cube'ss center, surrounded by AO_6 octahedra in interconnected vertices [85]. The formation and stability of perovskites depend on the dimensional and ionic properties of the A and B cations [86].

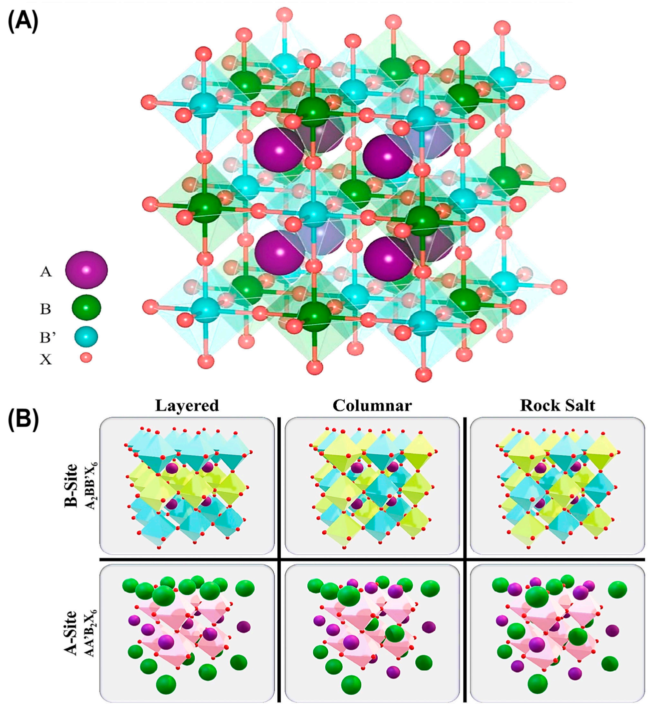

Figure 9. (**A**) Crystal structure of double perovskites. (**B**) Various types of cation orderings in A sites of double perovskite materials. Reproduced with permission from [87].

Oxides with perovskite-like structures are notable for their exceptional thermal stability, cost efficiency, enhanced oxygen mobility, and flexibility in structural modifications through the partial or complete replacement of cations [88]. These properties, combined with the unique characteristics of the individual metal components, offer several advantages for catalytic applications [89]. Specifically in heterogeneous catalysis, perovskite oxides have proven effective in the environmental remediation of antibiotics [90]. In the context of perovskite oxides, cation A is typically larger than cation B, which is fundamental for determining, for example, the catalytic capacity of these oxides in oxidation reactions [91]. Therefore, different synthesis methods were developed and evaluated regarding their influence on material properties and application. Currently, synthesis methods are divided into chemical and physical [92]. Chemical methods are the main approaches reported in the literature, for example, coprecipitation, hydrothermal, and sol–gel methods [93,94]. Physical methods include mechanochemical processes, high temperature, and radiation [95]. Figure 10 illustrates some synthesis methods. Therefore, several synthesis techniques may be used to prepare perovskite oxide-type materials. The choice of method depends on the desired properties of the material, the degree of control needed over its composition and structure, and the experimental conditions available.

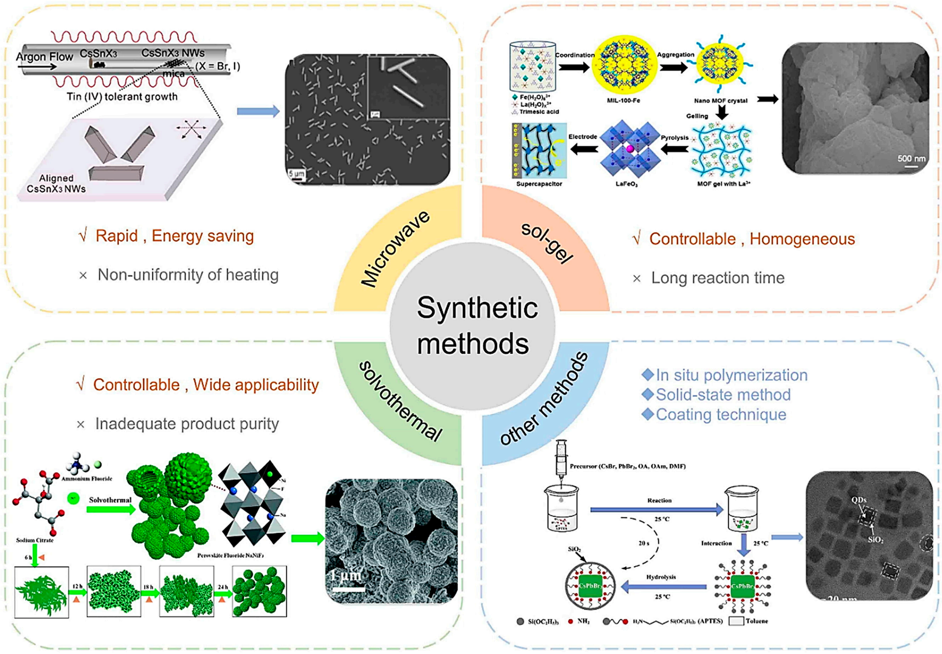

Figure 10. Main synthesis methods of perovskite-type materials. Reproduced with permission from [96].

$MnTiO_3$ perovskite nanodisks synthesized by the hydrothermal method were applied for the removal of several organic pollutants (methylene blue (MB), rhodamine B (RhB), congo red (CR), and methyl orange (MO)) [97]. The nanodisks showed characteristics of a well-crystallized material with an interplanar spacing of 0.352 nm composed of (0 1 2) rhombohedral lattice plane. In addition, the nanodisks presented several randomly aligned diffraction points. Kinetic studies showed degradation after 180 min of irradiation of 89.7%, 80.4%, 79.4%, and 79.4% of MB, RhB, MO, and CR, respectively. Optimized perovskites of $LaCo_{0.5}Fe_{0.5}O_3$ were hydrothermally synthesized and applied as a peroxymonosulfate activator to degrade bisphenol A in salt water [93]. The material had a micro spherical shape composed of 30 nm–40 nm nanorods with a porous structure, in which the perovskite lattice space was 0.275 Å, consistent with the lattice plane (1 1 0) of the rhombohedral phase. In addition, the system applied to remove the micropollutant showed a removal efficiency of 100%. The advantages of the hydrothermal method are the speed of the process and the ease of obtaining a homogeneous material. However, some limitations, such as high temperature and pressure, have hindered the methodology.

Nanopowders of $MnTiO_3$ and $MnTiO_3/TiO_2$ synthesized by the sol–gel method were applied to remove methylene blue in an aqueous solution under solar irradiation [98]. The particles showed crystallite size in the average range of 20 nm to 30 nm. Photodegradation of the pollutant using a few catalysts (0.005 g) achieved 70% and 75% removal rates for $MnTiO_3$ and $MnTiO_3/TiO_2$ after 240 min, respectively. $LaMnO_3$ nanoparticles sensitive to visible light synthesized via a sol–gel process using stearic acid as a complexing reagent was applied to degrade methyl orange [99]. The synthesized nanoparticles showed a pure perovskite structure with rhombohedral characteristics and average particle sizes from 20 to 30 nm. In addition, the material demonstrated a broad absorption band at 315 nm. The application in the degradation of the pollutant reached 98% in 90 min. Therefore, some advantages of the sol–gel method are the production of homogeneous materials and require low temperatures compared to other approaches. However, the disadvantages of the methodology have been the time needed for the process, and in some reported syntheses, it was necessary to use toxic reagents.

$CaMn_{0.3}Fe_{0.7}O_3$ perovskite synthesized using a solid state reaction route, consisting of mechanical ball milling and heating operation, was efficiently utilized in the in situ adsorption–oxidation of As(III) [95]. The maximum adsorption capacity on the metal was 120.78 $mg \cdot g^{-1}$, with the proportion of As(V) oxidized as high as 86.4% over a wide pH range. $La_xSr_{(1-x)}CoO_{3-\delta}$ perovskite-structured composites synthesized via mechanical milling without the use of organic solvent and no effluent generation were applied for the catalytic degradation of doxycycline via singlet oxygen without the addition of chemical reagents or lighting [100]. The TOC removal efficiency reached 89.64%, indicating that most pollutants may have been mineralized. Thus, the advantages of the solid-state synthesis method have been numerous, for example, simplicity, eco-friendliness, and no need to use reagents. However, high temperature for a long time and energy unfeasibility for large-scale production have been some disadvantages of the approach.

$Sr_{0.85}Ce_{0.15}FeO_{3-\delta}$ prepared by solution combustion synthesis from citric acid was tested in the abatement of orange II and rhodamine B [78]. The reported positive points of combustion synthesis are time and energy savings. On the other hand, the methodology is unsuitable for all types of materials. Porous $NiTiO_3$ nanorods synthesized through the sonochemical route followed by calcination were applied for the photocatalytic degradation of ceftiofur sodium [101]. The combination of peroxymonosulfate and the $NiTiO_3$ photocatalytic system showed mineralization of almost 97% of the pollutant under direct solar irradiation. The sonochemical route has some advantages, such as ease and speed. However, the disadvantages can be, for example, the requirement in some cases to produce the material over quite a long time. A microwave-assisted synthesis of $BaTiO_3$ nanospheres structured in perovskite via the peroxo route was applied to photodegradation methylene blue, malachite green, and alizarin red S dyes [102]. The highest dye decomposition efficiency (~100%) was successfully achieved by the material prepared using 10 min of irradiation. The advantages of microwave-assisted synthesis may be an alternative to conventional approaches. On the other hand, the disadvantages may be the high-power requirement, the need for heat absorption by the component, high energy cost, and infeasibility for production scaling. Therefore, the adequate choice of the material synthesis method is essential, as it directly impacts the characteristics of the perovskite oxide and, consequently, the application'ss performance. In this sense, evaluating the advantages and disadvantages of each approach requires a thorough evaluation to avoid setbacks.

5. Perovskite Oxide-Based Composites

Numerous strategies have been used to improve perovskite oxides for environmental applications, for example, producing magnetic composites to enable material separation [103]. In addition, new materials based on perovskite oxide and other components such as polymers, carbonaceous, and clays have been used to enhance performance in wastewater remediation [104]. The production of composites based on perovskite oxides offers several advantages over using oxide alone. These advantages are mainly related to the improvement of properties. Combining perovskite oxides with other materials may result in synergistic properties that the individual materials would not achieve, for example, improved electrical conductivity, adsorption capacity, catalytic activity, mechanical strength, chemical stability, and optical properties [105]. In photocatalytic applications, composites can expand the material'ss light absorption range, allowing a wider range of wavelengths to generate reactive oxygen species. That is, it can increase the effectiveness of the degradation of pollutants in wastewater.

5.1. Carbonaceous

A nanocomposite of manganese titanate, silver, and graphitic carbon nitride was synthesized for the photocatalytic degradation of tetracycline (Figure 11) [105]. The catalyst was produced via sol–gel, and the application of the catalytic system used simulated sunlight. The material showed a bandgap value of 2.5 eV with reasonable absorption in the UV and visible light spectrum through optical analysis. The photocatalytic activity of the composite was 61% in 120 min.

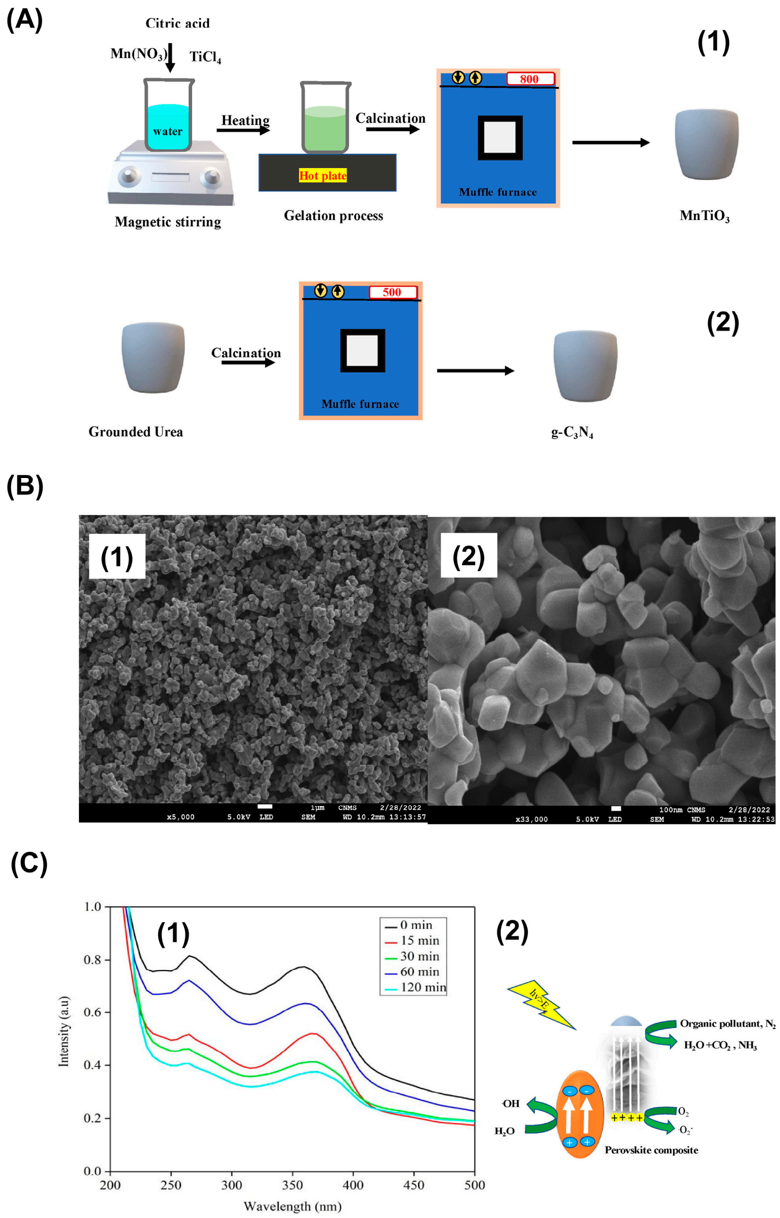

Figure 11. (**A**) Diagrammatic representation of the synthesis of (1) $MnTiO_3$ and (2) g-C_3N_4. (**B**) Depicting the FESEM image of $MnTiO_3$ zoomed (1) 5 K and (2) 33 K. (**C**) (1) Graphical representation of degradation of tetracycline within 120 min and (2) schematic representation of the mechanism of photocatalysis. Reproduced with permission from [105].

A composite of zinc stannate, iron, and graphitic carbon nitride was tested for the photocatalytic remediation of persistent organic compounds [104]. Zinc stannate perovskite was synthesized via coprecipitation. Through optical analysis, the material showed a bandgap value of 2.18 eV. The composite showed photocatalytic activity of 77% and 98% of methylene blue degradation under UV and visible light, respectively. In comparison, 67% of ciprofloxacin was degraded after 90 min under visible light. Composite material with the interface of lanthanum nickelate and reduced graphene oxide was used for sustainable decontamination of emerging pollutants under visible light photocatalysis [106]. About 83%

and 64% efficiency of photocatalytic degradation were observed in removing brilliant green and ciprofloxacin compounds in aqueous medium using the photocatalyst, respectively.

Producing composites of perovskite oxides with carbon-based materials can offer several advantages in many applications, especially in wastewater treatment. Carbon-based materials such as graphene, carbon nanotubes, and activated carbon have excellent electrical conductivity and charge transfer. By incorporating them into composites with perovskite oxides, it is possible to improve the electronic conductivity of the system, increasing the efficiency of reactions and electrochemical processes. Furthermore, carbon-based materials often have a high surface area due to their porous structure and nanometer size. Producing composites using carbonaceous materials may be a promising alternative for environmental applications.

5.2. Polymeric

Perovskite particles of $LaFeO_3$ immobilized on a commercial polymeric resin (Amberlite XAD-4) were tested in the photo-Fenton degradation of caffeine under visible light [107]. The immobilization of $LaFeO_3$ in the resin showed a significant change in the photocatalytic degradation of caffeine. The degradation rate in the presence of pure material (41.5%) increased to 78.5% after immobilization, suggesting that the synergistic effect of adsorption and photocatalysis played an essential role in the decaffeination process. In addition, reuse tests demonstrated that immobilization also facilitated the separation and stability of the catalyst, which can be used up to the sixth cycle.

Three-dimensionally ordered macroporous $LaFeO_3$ perovskite with different pore diameters using poly(methyl methacrylate) templates was tested for its catalytic activity for the combustion of carbon particles [108]. The catalytic activity of the material was improved from the new proposed template due to the presence of potassium cation in the reagent used as a polymerization initiator. Perovskites of $Nd_{0.9}TiO_3$ and $LaTiO_3$ were used to produce new hybrids based on polymers for the photodegradation of an organic dye [25]. Composites based on TMPTA showed the best performance in photocatalytic efficiency and stability. Adding 2% $Nd_{0.9}TiO_3$/polymer and 2% $LaTiO_3$/polymer in the aqueous solution under irradiation enhanced the photocatalytic process by 94% and 95%, respectively.

Therefore, producing composites of perovskite oxides with polymer-based materials combines the unique properties of both materials to create hybrids with improved performance and greater adaptability. Generally, polymeric materials are flexible and can be processed into different forms, including thin films, membranes, and coatings, which allows the synthesis of materials with specific formats that can meet the needs of different applications. Thus, they have been a promising strategy in developing new, more effective, and sustainable solutions for water purification.

5.3. Clays

Acid-modified natural zeolite doped with $LaFeO_3$ was tested in the photo-Fenton degradation of an organic compound (RhB) [109]. The material with the best performance was doped by approximately 30% by weight of perovskite. Furthermore, the best pollutant degradation condition (98.3%) was at 0.8 $g \cdot L^{-1}$ of catalyst, 10 $mg \cdot L^{-1}$ of RhB, 10 mM of H_2O_2, and an initial pH of 6. In another study, $LaFeO_3$/montmorillonite was evaluated on the degradation of rhodamine B under visible light irradiation [110]. The composite showed an overall removal rate of up to 99.34% after irradiation with visible light for 90 min. A composite of HZSM-5 zeolite and $SrTiO_3$ perovskite prepared by the sol–gel method was applied as a photocatalyst (30% $SrTiO_3$/0.3 HZSM-5) [111]. The specific surface area of the composite compared to pure oxide increased from 3.6 $m^2 \cdot g^{-1}$ to 155.5 $m^2 \cdot g^{-1}$. Furthermore, the photocatalytic degradation of the reactive brilliant red-X3B was almost 93.8% after 90 min of irradiation. Therefore, combining clays with perovskite oxides can provide numerous advantages, such as increasing the surface area and improving the process. Clays, such as montmorillonite, have a porous structure that results in a large surface area [112]. Therefore, incorporating perovskite oxides into the clay matrix may increase the available surface area of active sites, thus improving the contaminant holding capacity.

Perovskite oxide composites have emerged as a promising approach to the degradation of contaminants present in different environments [92]. Combining the unique properties of perovskite oxides with other materials such as polymers, carbon, and clays results in synergies that improve the efficiency and versatility of wastewater treatment and environmental remediation processes [113]. Thus, perovskite oxide composites offer significant advantages, such as increased surface area, improved adsorption, structural stabilization, ion exchange capacity, and resistance to degradation. By uniting the positive characteristics of different materials, hybrids make it possible to address complex contamination challenges more effectively and sustainably, where use in contaminant degradation is not limited to just one technique but encompasses a variety of processes, including photocatalysis, adsorption, and other approaches [25]. Application versatility makes perovskite oxide composites valuable materials to tackle water pollution.

6. Challenges, Future Perspectives, and Rethinking Treatment Strategies in Antibiotics Remediation

Hybrids of perovskite oxides and other materials have emerged as a promising area in wastewater remediation, presenting significant advantages [20]. However, the field also faces critical challenges. The stability of perovskite oxide composites and other materials under different environmental conditions has still been a critical challenge, as it is critical to ensure that the structure and properties of composite materials are maintained over time for effective and consistent remediation [87]. In addition, the selection of materials and the ideal proportion between the components have been studied by specialists so that the composites reach the maximum performance. Therefore, a deep understanding of the interactions between components and how they affect properties and efficiency is required to optimize any material.

Rethinking strategies for remediating antibiotic-contaminated water and other emerging pollutants with sustainable approaches is paramount for the long-term protection of the environment and human health. An essential guideline is to prevent pollution in water from the source, which involves implementing proper disposal practices, including programs to collect and safely dispose of expired or unused materials (e.g., drugs). In addition, educational campaigns about the impact of antibiotics on the environment may be essential options to make the public and health professionals aware of the importance of avoiding the improper release of drugs in nature. Promoting the responsible use of antibiotics in human and veterinary medicine may also contribute to reducing the presence of antibiotics in the environment. Appropriate prescription of antibiotics only, when necessary, adherence to recommended doses, and full use of prescribed treatment should be standard practices for the entire population.

In this sense, research in developing new materials and improving existing ones, aiming at an even greater efficiency in the remediation of contaminants present in wastewater, has been continuously reported. In addition, custom applications to target specific contaminants have been trending in the field, where future research may direct the creation of highly selective materials for certain pollutants, increasing efficiency and minimizing unwanted impacts [62,70,114,115]. However, some gaps have been highlighted, such as large-scale applications and understanding pollutant degradation mechanisms. The production and application of economically viable perovskite oxide hybrids on an industrial scale, enabling their widespread adoption, is still a step to be overcome, as most research is at the laboratory level. In addition, a better understanding of the mechanisms of degradation and removal of contaminants by composites of perovskite oxides to make the process more intelligent and effective for materials for specific applications may also be a promising alternative for studies. Therefore, composites of perovskite oxides and other materials have the potential to play an important role in wastewater remediation, contributing to the solution of pressing environmental challenges. While the technical and scientific challenges are significant, prospects indicate promising advances and innovations that could revolutionize how we approach the remediation of contaminated water resources.

To address the problem of antibiotics and other emerging pollutants in water, it is critical to develop and implement green technologies for treatment processes [43,46]. This includes using remediation techniques that minimize energy consumption, waste generation, and toxic by-product emissions, as well as research into advanced oxidation methods using renewable energy sources such as sunlight and the development of more efficient catalysts. However, it is essential to note that the successful implementation of sustainable approaches requires collaboration among governments, research institutions, industry, professionals, and society at large. Therefore, investing in research and the development of sustainable technologies, raising public awareness, and adopting appropriate policies are essential to effectively address the environmental challenges posed by emerging pollutants and ensure the health of ecosystems and future generations.

7. Conclusions

Perovskite oxides emerge as promising agents in treating environments contaminated by antibiotics, offering optimistic prospects for the remediation of these pollutants. Its catalytic capacity and specific properties show significant potential in developing effective strategies to address environmental contamination caused by antibiotic residues. This innovative approach paves the way for promising perspectives in environmental remediation and highlights the continued importance of research in this field. In addition, composites of perovskite oxides and other materials prove to be an auspicious and innovative approach to wastewater remediation. This represents a significant step towards more effective and sustainable solutions to contemporary environmental challenges. Combining the unique properties of perovskite oxides with various complementary materials, such as polymers, carbon, and clays, has resulted in composites that exhibit exceptional synergies, expanding the scope and efficiency of remediation processes. While the field is teeming with opportunities, it also faces several challenges that require attention. The stability and durability of perovskite oxide hybrids under varying environmental conditions may be crucial for practical application and long-term effectiveness. In addition, precisely optimizing the composition and proportions of constituent materials has been essential in maximizing synergy and superior performance in contaminant remediation.

Antibiotic and other emerging pollutant treatment techniques represent a crucial area of research and development to address the growing challenges of the presence of drugs in the environment. While much study remains to be carried out, significant progress has been made in developing practical and sustainable remediation approaches. However, it is essential to highlight some promising future perspectives, such as advances in green technologies, investment in combined remediation processes, promoting the improvement of biological techniques, the effective monitoring of antibiotics and antibiotic resistance genes in nature, and the development of increasingly intelligent waste management systems.

The prospects in both fields are promising, with an increasing focus on developing more efficient, pollutant-specific, and highly selective materials. Exploring degradation and adsorption mechanisms is also vital to direct research and the design of more effective perovskite oxide hybrids and emerging pollutant treatment techniques. In addition, the integration of materials with existing technologies and production scalability are areas of development that can amplify the impact of hybrids and treatment techniques in wastewater remediation on a global level.

Ongoing research in bioremediation and developing green and sustainable technologies will continue to drive the efficiency and cost effectiveness of remediation techniques in both fields. Using renewable energy sources, genetic engineering, advanced analytical techniques, data analytics, and predictive modeling all play critical roles in addressing environmental challenges. Awareness and continued education about the environmental impacts of contaminants, whether they be antibiotics or other pollutants, are essential for a systematic approach to mitigating the problems at hand. Therefore, the fields of perovskite oxide hybrids and treatment techniques are ever evolving, driven by the goal of protecting the environment and human health. With continuous research efforts, collaboration between different sectors, and coordinated actions at a global level, it is possible to address the challenges associated with contaminants in water and ensure a more sustainable and prosperous future.

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