separations

MDPI

Review

Defect, Pore, and Surface Engineering of Nanomaterials for Wastewater Treatment: A Review

Haiqing Hao [1], Tiancheng Zhang [2], Qing Li [2], Guoli Zhou [1] and Hao Zhang [2,*]

[1] State Key Laboratory of Critical Metals Beneficiation Metallurgy and Purification, Zhengzhou 450001, China
[2] Jiangxi Research Institute, Key Laboratory of Separation and Processing of Symbiotic-Associated Mineral Resources in Non-Ferrous Metal Industry, Engineering Technology Research Center for Comprehensive Utilization of Rare Earth—Rare Metal—Rare Scattered in Non-Ferrous Metal Industry, School of Chemical & Environmental Engineering, China University of Mining & Technology (Beijing), Beijing 100083, China
* Correspondence: zhanghaoe66@163.com

Abstract

Nanomaterials offer high specific surface area and tunable surface chemistry. They can be used as promising adsorbents, photocatalysts, and membrane components for wastewater treatment. However, problems of low efficiency and low recyclability limit the practical application of some nanomaterials. This review summarizes their use for inorganic and organic pollutant removal and examines defects. The modification and controllable construction of nanomaterials in terms of defect regulation, pore structure modification, and surface modification are also summarized. Pore and surface engineering strategies are discussed through a structure–property–performance framework. Then, improvements in pore and surface structures are investigated in relation to the controllable construction of nanomaterials. The evidence indicates that performance gains must be evaluated alongside regeneration, active-material leaching, transformation products, and energy demand. Future progress depends on reproducible comparisons, realistic wastewater testing, and recovery-by-design rather than removal efficiency alone.

Keywords: adsorption; photocatalysis; defect engineering; surface functionalization; membranes

1. Introduction

With rapid population growth and industrial development, water pollution is becoming increasingly severe, and the demand for clean water resources has increased. Pollutants released in wastewater can threaten human health and aquatic ecosystems [1–3]. Comprehensive treatment and recycling of wastewater are therefore important for ecosystem protection and sustainable industrial production.

The composition of wastewater is extremely complex and varies depending on its source. Common pollutants in wastewater can be categorized into inorganic and organic pollutants [4]. Inorganic pollutants include anionic and cationic inorganic pollutants. F^-, $NO_3{}^-$, $PO_4{}^{3-}$, arsenates, and chromates are anionic inorganic pollutants [5–8], while Pb^{2+}, Hg^{2+}, Cd^{2+}, Cu^{2+}, Ni^{2+}, and Co^{2+} are cationic inorganic pollutants [9–11]. Organic pollutants contain synthetic dyes, organic pharmaceuticals, etc. [12,13].

Given the complexity and variability of wastewater composition, research on effective treatment methods to remove harmful substances from wastewater is prerequisite for achieving wastewater recycling and is also essential to ensuring the sustainable use of water resources and promoting green development [14].

Check for updates

Academic Editor: Chunlin He

Received: 19 September 2026
Revised: 18 October 2026
Accepted: 19 October 2026
Published: 22 October 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Conventional wastewater treatment methods, including adsorption, sedimentation, and coagulation–flocculation, often suffer from drawbacks such as high costs and low efficiency [15–17]. Therefore, research on new technologies and methods for wastewater treatment is urgently needed to achieve comprehensive wastewater recycling and utilization. Due to the advantages of high efficiency and strong applicability, nanotechnology is an innovative approach for efficient wastewater treatment [18,19]. Nanotechnology makes use of nanomaterials and their unique structural properties to make up for the shortcomings of conventional wastewater treatment methods. Thus, both the effectiveness and efficiency of wastewater treatment can be improved. Nanotechnology has been widely applied in membrane separation, catalysis and photocatalysis, pollutant adsorption, and other areas to enhance wastewater treatment efficiency [20–22].

Numerous reviews have summarized MOFs, graphene, photocatalysis, and membranes for treatment of heavy metals and organic pollutants. This paper reviews the controllable construction and modification of nanomaterials for improving performance. A structure–property–performance framework is designed to connect the regulation of crystal structure defects, pore structure, and surface structure modifications. Recent strategies are summarized. It is intended to move the review from a catalog of materials toward design rules that can guide material selection and design.

2. Application of Nanomaterials in Wastewater Treatment

Compared with traditional materials, nanomaterials can provide a high specific surface area, tunable adsorption sites, and catalytic activity [23,24]. They are therefore a major research focus [25,26].

2.1. Application of Nanomaterials in Inorganic Wastewater Treatment

Nanomaterials exhibit strong adsorption capacity for inorganic ions, which is influenced by surface functional groups (such as –OH), accessible surface area, and pollutant speciation. They have been investigated for wastewater containing heavy metal ions, rare earth metal ions, arsenic, phosphate ions, cyanide ions, etc. [27–31].

A functional ligand-immobilized mesoporous silica-based nano-conjugate material was prepared by Md. Rabiul Awual et al. to achieve simultaneous detection and removal of Co(II) from wastewater [32]. The surface of the novel nano-conjugate material provides multiple adsorption sites for Co(II) and enables selective capture the trace Co(II) ions. The maximum adsorption capacity for Co(II) reached 170.17 mg/g. Magnetic iron oxide nanoparticles were used to remove arsenic from wastewater by María Martínez-Cabanas [33] and Sneha Lunge [34]. These nanoparticles can selectively adsorb As(III) and As(V) from water, with adsorption capacities reaching 188.69 mg/g and 153.8 mg/g, respectively. Moreover, compared with conventional adsorbents, the treatment costs of arsenic-containing wastewater using these magnetic iron oxide nanoparticles were reduced, and the efficiency was improved. A hybrid iron oxide nanoparticle–zeolite was synthesized by Qianyu Xu et al. to remove ammonia and phosphate simultaneously [35]. Based on the cation exchange between NH_4^+ and the material surface, and the chemical interaction between PO_4^{3-} and the material surface, the removal efficiencies of NH_4^+ and PO_4^{3-} reached 43.3% and 99.8%, respectively.

In addition, nanomaterials can provide sites for the photocatalytic reduction of metal ions (Cr(VI), Hg^{2+}, UO_2^{2+}, etc.) [36,37]. Typically, nanomaterials used for the photocatalytic reaction of inorganic pollutants are mostly metal oxide nanoparticles with semiconductor properties. Arjun Behera et al. [38] employed $ZnFe_2O_4$-C composite nanomaterials to catalytically reduce Cr(VI) in wastewater. $ZnFe_2O_4$-C composite nanomaterials exhibit low photoexcited electron–hole recombination and high charge transfer properties. More-

over, they enhance visible light absorption and improve charge carrier separation. Under solar light irradiation, the catalytic reduction of Cr(VI) (concentration 10 mg/L) reached 82% within 60 min with the nanomaterials. Yang Zhang et al. [39] used silicon-based nano-titanium composites to treat cyanide-containing wastewater. With the composite functional material, 99.8% of cyanide was decomposed after 135 min of illumination. The copper cyanide complexes and zinc cyanide complexes were ultimately broken down into CO_2, NO_2, Cu^{2+}, and Zn^{2+}.

The nanomaterials used for inorganic wastewater treatment are summarized in Table 1.

Table 1. Comparative summary of nanomaterials for inorganic ion removal.

Inorganic Ions/Pollutant	Nanomaterial Used	Ref.
Pb^{2+}	Graphene/GO, CNTs, MOFs, ZIFs, LDHs, magnetic composites, nano clays	[40–46]
Cu^{2+}	GO/rGO, CNTs, MOFs, magnetic nanocomposites	[47–50]
Cd^{2+}	MnO_2/CNT, magnetic nanocomposites, GO, zeolite nanoparticles, MOFs	[51–53]
Hg^{2+}	Functionalized graphene, MXene, sulfur-containing nanomaterials, MOFs, magnetic composites	[54–57]
Cr(VI)	Fe_3O_4/Fe^0 nanoparticles, graphene-based nanocomposites, MXenes, MOFs	[58–61]
As(III)/As(V)	Fe_3O_4, FeOOH, ferrihydrite nanoparticles, Zr/Fe oxides, MOF composites	[62–64]
F^-	Al_2O_3, Fe_2O_3/FeOOH, CeO_2, ZrO_2, MgO, TiO_2, MOFs	[65–68]
PO_4^{3-}/phosphate	LDHs, Fe/Al oxides, MOFs, MOF-derived metal/carbon composites, layered nanomaterials	[69–72]
NO_3^-	Functionalized metal oxides/hydroxides, layered materials, nano-chitosan/clay composites, nanocomposites	[73,74]
Se(IV)/Se(VI)	Fe-based composites, MOFs, modified polymers	[75–77]
U(VI)/radionuclides	MXenes, graphene composites, Fe_3O_4, MOFs, LDHs, MnO_2	[78–81]

2.2. *Application of Nanomaterials in Organic Wastewater Treatment*

Organic pollutants in wastewater include petroleum hydrocarbons, detergents, plastics, pesticides, dyes, and microplastics, many of which are toxic, persistent, or suspected carcinogens. They pose a threat to the survival and life of humans and other living organisms [82]. Nanomaterials can be used as photocatalysts, adsorbents, nanocomposite membranes, or membrane support materials to improve the efficiency of organic wastewater treatment [83–85].

Nanomaterials used as photocatalysts often possess significant photogenerated electron–hole separation characteristics. They are capable of highly efficient photocatalytic degradation of organic pollutants. Esraa M. El-Fawal et al. [86] deposited AlZnO onto carbon-based substrates and employed the composite nanomaterials to treat textile wastewater containing methylene blue, methyl orange, Astrazone Blue FRR, and Rhodamine B. Both AlZnO@G(AlZnO@graphene) and AlZnO@CN(AlZnO@Carbon nitride) nanomaterials can enable efficient, in situ solar-assisted adsorption/photocatalytic degradation of dyes in textile wastewater. Dye molecules were adsorbed on AlZnO@G through physical interactions. Moreover, the AlZnO@CN exhibited strong photocatalytic degradation efficiency. The dye degradation ratio reached 93.8% within 60 min using AlZnO@CN. Di Gu

et al. [87] synthesized C/TiO_2/Ti composite nanomaterials for organic wastewater degradation by depositing molten carbonate onto TiO_2 nanotubes. The composite nanomaterial enables efficient oxidation of wastewater by utilizing solar and electrical energy, and can be applied to organic wastewater treatment. Under the multifield-driven thermo-photoelectrochemistry field, nitrobenzene in wastewater could be efficiently degraded with a degradation efficiency of 84.9%.

The excellent adsorption performance of nanomaterials benefits from their active surface chemistry. Guanrong Yang et al. [88] employed a novel magnetic nanomaterial, Co@CoO/NC, to adsorb Rhodamine B and tetracycline from wastewater. It features high efficiency, stability, and ease of recovery, enabling effective treatment of organic wastewater. With the new nanomaterial, the adsorption capacities of Rhodamine B and tetracycline reached 679.56 mg/g and 385.60 mg/g, respectively. The primary driving forces for the adsorption of the two organic contaminants on the material surface are hydrogen bonding and π-π interactions. In addition, due to the presence of abundant CoO groups on the surface of Co nanoparticles, ion exchange and complexation also serve as driving forces for tetracycline adsorption on the material surface.

Membrane separation is an effective option for treating organic wastewater, with advantages such as low cost and strong operability [89]. Membrane materials and supporting materials are key factors. Heba Isawi [90] prepared nanocomposite polyvinylidene fluoride (PVDF) membranes by incorporating vermiculite nanoparticles into PVDF membranes to remove dyes, including malachite green, methylene blue, and Congo red, from wastewater. The vermiculite nanoparticles could significantly enhance the antifouling properties and mechanical strength of the PVDF membranes, and greatly improve the removal efficiency for the dyes. Therefore, nanomaterials can effectively enhance the performance of membrane materials and improve the efficiency of membrane-based organic wastewater treatment [91–93].

Giuseppe Vitiello et al. [94] prepared a novel hybrid nanomaterial with humic acid and nano-titanium dioxide, which was used as an antibacterial agent to treat Gram (−) pathogens and antibiotics in wastewater. The novel nanomaterial can selectively remove amoxicillin and tetracycline antibiotics from wastewater. Due to the increase in reactive hydroxyl oxygen, the reactive oxygen species (ROS)-mediated antibacterial activity of the novel nanomaterial was enhanced, resulting in improved antibacterial efficacy against pathogens in wastewater. Huan Yi et al. [95] prepared a 2D biomimetic hemin–bismuth tungstate composite with an interlayer spacing of 0.35 nm for the photocatalytic degradation of tetracycline antibiotics. The novel 2D nanomaterial presents strong binding affinity and high photocatalytic activity in tetracycline degradation by taking full advantage of the synergistic effect of artificial enzymes and photocatalysts. It provides a solution for the degradation of biological wastewater.

The nanomaterials used for organic wastewater treatment are provided in Table 2.

Table 2. Comparative summary of nanomaterials for organic pollutant removal.

Organic Pollutant	Nanomaterials Used	Ref.
Synthetic dyes (methylene blue, Rhodamine B, methyl orange, Congo red, etc.)	GO/rGO, CNTs, MXenes, MOFs, metal oxides, magnetic nanocomposites	[96–101]
Pharmaceuticals (antibiotics (tetracycline, ciprofloxacin, sulfonamides, etc.), analgesics, anti-inflammatory drugs)	MOFs, GO/rGO, MXenes, CNTs, TiO_2, magnetic nanocomposites	[102–107]
Pesticides/herbicides	CNTs, GO, carbon dots, MOFs, biochar nanocomposites, metal-oxide nanocomposites	[108–110]

Table 2. *Cont.*

Organic Pollutant	Nanomaterials Used	Ref.
Phenols and phenolic compounds	GO/rGO, CNTs, activated-carbon nanocomposites, MOFs, TiO_2, ZnO, Fe-based nanoparticles	[111–113]
Endocrine-disrupting compounds (bisphenol A, hormones, alkylphenols)	GO, MOFs, CNTs, molecularly functionalized nanoparticles, TiO_2	[114–117]
PFAS/fluorinated organic contaminants	Functionalized carbon nanomaterials, MOFs, polymeric nanocomposites, membrane nanomaterials	[118–121]

3. Modification and Controllable Construction of Nanomaterials

The properties of nanomaterials, such as size, surface area, shape, aspect ratio, surface charge, and solubility, determine their physical, chemical, and biological characteristics, which in turn determine their applications in wastewater treatment [122]. The controllable construction of nanomaterials is a fundamental approach to improving their catalytic and adsorptive properties [123–125].

3.1. Regulation of Crystal Structure Defects

The arrangement of particles in a crystal determines its structural characteristics. Changes in particle arrangement can induce alterations in the crystal structure, leading to the formation of crystal structure defects, which in turn affect the performance of nanomaterials.

Defects, including vacancies, substitutional atoms, interstitials, dislocations, and low-coordination sites, can change adsorption energy, surface charge, band structure, oxygen activation, and electron–hole recombination. In photocatalysts, oxygen vacancies or anion vacancies can create electronic states that improve visible light utilization and interfacial charge transfer, but excessive defect density may instead act as recombination centers. In adsorbents, defective coordination environments can increase the density of unsaturated metal sites and strengthen oxyanion or metal-ion binding. Different strategies have been proposed for defect regulation [126]. Heteroatom doping has been used to narrow effective band gaps and promote interfacial electron transfer [127]. N, S, P, B, or transition-metal incorporation can tune charge density and adsorption selectivity. Additionally, vacancy engineering also serves to expose active sites and alter local electronic states [128]. The balance among dopant states, oxygen vacancies, and charge carrier recombination determines net activity. Heterojunction construction is another defect/electronic structure strategy [129]. Type-II heterojunctions spatially separate photogenerated electrons and holes, whereas Z-scheme and S-scheme architectures are designed to retain strong redox potentials while suppressing recombination [130].

Molten salt-assisted synthesis is one of the effective methods for regulating the defect structures of nanomaterials. Weimin Du et al. [131] prepared ZrO_2/Dy_2O_3 solid solution nanomaterials with different defect structures via a molten salt-assisted method, and found that $Zr_{0.8}Dy_{0.2}O_{2-\delta}$, which possesses a specific defect structure and high specific surface area, exhibits good photocatalytic activity and has broad application prospects in dye wastewater treatment. When ion substitution occurs in the lattice of ZrO_2/Dy_2O_3, the lattice parameters remain unchanged, while the charge compensation effect generates oxygen vacancy defects and interstitial oxygen defects in the crystal. $Zr_{0.8}Dy_{0.2}O_{2-\delta}$ has a high concentration of oxygen defects and exhibits strong visible light absorption, thus demonstrating good photocatalytic degradation activity toward Rhodamine B. Further-

more, Weimin Du et al. [132] prepared RE/ZrO_2 nanomaterials with defect structures to confirm that the interplanar spacing of the nanomaterials increases with the increasing molar ratio of rare-earth elements. This resulted in differences in the monoclinic defect structures and electronic configurations. Consequently, the nanomaterials exhibit different visible light absorption characteristics, ultimately leading to differences in their photocatalytic activity.

Adjusting the synthesis environment is another effective approach to regulate the formation of crystal structure defects in nanomaterials. Can Wu et al. [133] introduced Mg^{2+} into the spinel ferrite lattice by altering the solvent conditions during nanomaterial synthesis, thereby regulating the formation of defect structures in $MgFe_2O_4$ and enhancing the removal of As(V) from water. By utilizing intrinsic vacancy defects in the spinel ferrite crystal, as well as defect clusters formed by atom doping, the concentration of –OH groups adsorbed on the material surface was increased. The increased amount of surface hydroxyl groups, the formation of tridentate hexanuclear surface complexes, as well as the formation of excess Mg-OH surface hydroxyl groups and As-Mg monodentate mononuclear surface complexes ensure the superior adsorption capacity. As a result, the adsorption of As(V) from water onto the nanomaterials was enhanced.

Both fine grinding and sonication can alter crystal structure parameters by applying stress to the crystal structure of nanomaterials, or by introducing impurities into the lattice. Christos A. Aggelopoulos et al. [134] introduced volume defects into the structures of nano-ZnO and nano-TiO_2 through fine grinding, which induced phase transitions and partial amorphization in the material lattice and achieved mechanical activation of the nanomaterials. As a result, the photocatalytic activity of nano-ZnO and nano-TiO_2 for the degradation of methylene blue was improved.

In addition, hydrogenation heat treatment, high-temperature quenching, the introduction of modifiers during the synthesis process, and post-synthetic modification can all enhance the formation of defects in crystals, thereby improving the catalytic activity, photocatalytic activity, and electrical conductivity of nanomaterials [135,136].

3.2. Pore Structure Modification

The pore structure, pore size, and pore distribution of nanomaterials are the main factors affecting material performance [137]. According to IUPAC, pores are classified as micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm) [138]. Pore size relative to pollutant molecular size determines accessibility, diffusion resistance, size exclusion, and the probability that active sites are reached. Micropores can provide strong confinement and high adsorption potential, whereas mesopores and macropores can shorten diffusion pathways and facilitate the transport of larger molecules. Different methods, such as templating, activation, etching, pillaring, partial framework removal, self-assembly, and controlled calcination, can achieve the regulation of pore structure and pore size in nanomaterials [139–141].

The formation of pore structures can significantly improve the removal efficiency of nanomaterials for specific substances in wastewater. Yan Cui et al. [142] prepared magnetic carbon nanospheres (MCNSs) doped with Fe_3O_4 nanoparticles via a solvothermal synthesis method, and introduced pore structures into the magnetic carbon nanospheres through KOH activation, which increased the specific surface area of the MCNSs. Subsequently, oxygen-containing functional groups were also introduced onto the pore walls and the surface of the magnetic carbon nanospheres via HNO_3 acidification. The abundant micropores and mesopores, as well as the oxygen-containing functional groups, enhanced the acid–base interactions between the magnetic carbon nanospheres and quinoline. The adsorption capacity of the magnetic carbon nanospheres for quinoline increased from 99.43

to 297.21 mg/g. In addition, nanomaterials with different pore structures exhibit different efficiencies in wastewater treatment. Yan Li et al. [143] prepared nickel foam-supported $NiCo_2O_4$-nanoflake-coated nickel foam and $NiCo_2O_4$-nanowire-coated nickel foam via a hydrothermal synthesis method. The former formed a closed pore structure composed of $NiCo_2O_4$ nanoflakes, while the latter formed an open pore structure composed of $NiCo_2O_4$ nanowires. Compared with the open-pore structure, the closed-pore structure can better trap water molecules, forming a more stable superhydrophilic/underwater superoleophobic interface, and exhibiting a larger oil contact angle and lower underwater oil adhesion, thus enabling better oil–water separation.

The shape and distribution of pore structures are important factors affecting the adsorption efficiency and reaction efficiency of nanomaterials. Shima Barakan et al. [144] modified the pore structure of nano-bentonite using $AlCl_3 \cdot 6H_2O$ and $FeCl_3 \cdot 6H_2O$, along with dodecylamine and tetraethyl orthosilicate, under microwave and ultrasonic irradiation, producing mixed aluminum- and iron-pillared nano-bentonite and porous nano-bentonite heterostructures. The introduction of pillared structures and porous modifications increased the number of active sites on the nanomaterial surface, thereby improving the removal efficiency of arsenic species from wastewater. Dawei Ji et al. [145] employed polymerization-induced phase separation to modify the pore structure of polysulfone (PSF) nanofiltration membranes, using air as the pore-forming fluid and graphene oxide (GO) as an additive. Under the synergistic effect of air and graphene oxide, the PSF/GO hollow fiber membranes formed a unique dense–loose structure. The dense outer surface and the loose inner surface generated large pores. They also produced small pores distributed across the cross-section. The unique dense–loose structure of the PSF/GO nanofiltration membranes significantly improved the material's hydrophobicity, surface charge, and mechanical properties. Moreover, after pore structure modification, the removal rate of Congo red by the material was enhanced, reaching up to 99.9%.

Regulation of the pore structure of nanomaterials can alter the functions of the inner surface of the nanopores in terms of guest recognition, catalysis, ion and electron transport, energy transfer, and interface construction, thereby significantly improving the adsorption, electrical conductivity, and chemical stability of nanomaterials [146,147]. In addition, morphology control should be considered alongside pore size [148]. Nanorods, nanosheets, hollow structures, core–shell particles, and yolk–shell architectures can change exposed facets, internal voids, diffusion paths, and catalyst stability [149].

3.3. Surface Modification

Surface modification of nanomaterials can improve their properties, such as reactivity and biocompatibility [150]. The common methods used for surface modification include grafting, covalent coupling, ligand exchange, polymer coating, surfactant assembly, and surface termination engineering [151,152]. The objective is to tune charge, hydrophilicity/hydrophobicity, specific binding, redox activity, and resistance to fouling or dissolution.

Coupling agents and surfactants are commonly used to modify the surface of nanomaterials. Yanru Zhang et al. [153] modified nano-magnetite with 3-(diethylamino) propyltrimethoxysilane and glycine. Carboxyl and amino groups were introduced onto the nanomaterial surface. As a result, the adsorption of anionic dyes under strongly acidic conditions and cationic dyes under strongly alkaline conditions on the materials was enhanced. Ghomashi et al. [154] modified nano-clinoptilolite zeolite with hexadecyltrimethylammonium ($HDTMA^+$). $HDTMA^+$ is a quaternary ammonium surfactant. At sufficient loading, it can form an admicelle/bilayer on the zeolite, exposing positively charged headgroups that capture anions through anion exchange. Nejat Sadati Behbahani et al. [155] modified

nano-magnetite particles (MNPs) covalently with 3-aminopropyltriethoxysilane (APTES) and dicarboxyl poly(ethylene glycol) (HOOC-PEG-COOH) sequentially to strengthen the complexation between the nanomaterials and lead ions in water. As a result, the removal rate of lead from wastewater was improved. Compared with oleic acid-modified MNPs and physically PEG-modified MNPs, the covalently modified MNPs (MNPs-APTES-PEG) provided active sites for cation adsorption on the material surface, which increased the lead ion removal rate from water to 81%.

Surface modification can significantly improve the properties and applications of nanomaterials. It also brings challenges such as poor degradability or low stability. Moreover, the surface modification processes can complicate production and pose problems for subsequent manufacturing. Therefore, efficient and economical surface modification methods are essential for ensuring the high-performance industrial application of nanomaterials [156–158].

4. Conclusions

Owing to their unique physicochemical and electromagnetic properties, as well as their ease of functionalization, nanomaterials have become one of the most promising classes of materials in water treatment. The modification and controllable construction of nanomaterials have significantly improved their performance and consolidated their important position in the field of wastewater treatment. However, challenges remain in the application of nanomaterials in water treatment due to uncertainties regarding toxicity, stability, secondary pollution, and recyclability. Therefore, the design, modification, and controllable construction technologies for nanomaterials need to be further developed. Consequently, research should focus on the physicochemical characteristics of different wastewaters, with the goal of preparing nanomaterials that are efficient, economical, non-toxic, environmentally adaptable, and easy to recover and recycle. It is necessary to improve nanomaterial preparation and modification technologies, expand the application of nanomaterial technology in wastewater treatment, and enhance wastewater treatment efficiency.

5. Challenges and Perspectives

Despite considerable progress in nanomaterial-based wastewater treatment, several challenges remain before practical application. First, the performance of nanomaterials under laboratory conditions may not be maintained in real wastewater because of competing ions, dissolved organic matter, and variations in pH and ionic strength. Second, nanoparticle separation, material recovery, and regeneration remain challenging, while structural degradation and active-component leaching may reduce long-term stability and cause secondary pollution. In addition, pollutant-loaded adsorbents, catalytic transformation products, and membrane concentrate require appropriate management. The complexity and cost of material synthesis, limited continuous flow validation, and insufficient assessment of environmental safety and life cycle impacts further hinder large-scale implementation.

Future work should focus on integrating defect engineering, pore structure regulation, and surface modification to achieve pollutant-specific selectivity, efficient mass transfer, and enhanced stability. Material design should incorporate recovery and regeneration strategies from the outset, while systematic evaluation using real wastewater, long-term cycling, and continuous-flow experiments is needed to verify practical performance. Standardized reporting of experimental conditions and performance metrics, together with assessments of nanoparticle leaching, ecotoxicity, techno-economic feasibility, and life cycle impacts, will enable more reliable comparisons among different materials.

Author Contributions: H.H.: Conceptualization, Investigation, Data curation, Writing-original draft; T.Z.: Data curation, Validation; Q.L.: Formal analysis, Validation; G.Z.: Investigation, Visualization; H.Z.: Supervision, Methodology, Funding acquisition, Writing-review & editing. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported by the National Natural Science Foundation of China (No. 52304280), Jiangxi Research Institute's Independent Research Project (JX25019), and the Fundamental Research Funds for the Central Universities (2025XJHH01, 2025ZKPYHH03).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Jain, K.; Patel, A.S.; Pardhi, V.P.; Flora, S.J.S. Nanotechnology in wastewater management: A new paradigm towards wastewater treatment. *Molecules* **2021**, *26*, 1797. [CrossRef]
2. Oladimeji, T.E.; Oyedemi, M.; Emetere, M.E.; Agboola, O.; Adeoye, J.B.; Odunlami, O.A. Review on the impact of heavy metals from industrial wastewater effluent and removal technologies. *Heliyon* **2024**, *10*, e40370. [CrossRef]
3. Wear, S.L.; Acuña, V.; McDonald, R.; Font, C. Sewage pollution, declining ecosystem health, and cross-sector collaboration. *Biol. Conserv.* **2021**, *255*, 109010. [CrossRef]
4. Ghosh, A.; Nayak, A.K.; Pal, A. Nano-particle-mediated wastewater treatment: A review. *Curr. Pollut. Rep.* **2017**, *3*, 17–30. [CrossRef]
5. Vo, H.N.P.; Ngo, H.H.; Guo, W.; Liu, Y.; Chang, S.W.; Nguyen, D.D.; Nguyen, P.D.; Bui, X.T.; Ren, J. Identification of the pollutants' removal and mechanism by microalgae in saline wastewater. *Bioresour. Technol.* **2019**, *275*, 44–52. [CrossRef]
6. Damtie, M.M.; Woo, Y.C.; Kim, B.; Hailemariam, R.H.; Park, K.-D.; Shon, H.K.; Park, C.; Choi, J.-S. Removal of fluoride in membrane-based water and wastewater treatment technologies: Performance review. *J. Environ. Manag.* **2019**, *251*, 109524. [CrossRef]
7. Ghimire, K.N.; Inoue, K.; Yamaguchi, H.; Makino, K.; Miyajima, T. Adsorptive separation of arsenate and arsenite anions from aqueous medium by using orange waste. *Water Res.* **2003**, *37*, 4945–4953. [CrossRef]
8. Jin, L.; Sun, G.; Zhang, H.; Yuan, G.; Ma, J.; Peng, X.; Cui, Y. Design of a preorganized adsorbent for the removal of chromate from wastewater under neutral conditions. *Chem. Commun.* **2019**, *55*, 3485–3488. [CrossRef]
9. Li, D.; Zhou, L. Adsorption of heavy metal tolerance strains to Pb^{2+} and Cd^{2+} in wastewater. *Environ. Sci. Pollut. Res.* **2018**, *25*, 32156–32162. [CrossRef]
10. Phoungthong, K.; Suwunwong, T. Magnetic biochar derived from sewage sludge of concentrated natural rubber latex (CNRL) for the removal of Al^{3+} and Cu^{2+} ions from wastewater. *Res. Chem. Intermed.* **2020**, *46*, 385–407. [CrossRef]
11. Ge, Y.; Yuan, Y.; Wang, K.; He, Y.; Cui, X. Preparation of geopolymer-based inorganic membrane for removing Ni^{2+} from wastewater. *J. Hazard. Mater.* **2015**, *299*, 711–718. [CrossRef]
12. Zhuang, Y.; Jiang, R.; Wu, D.; Yu, Y.; Wang, J. Selenocarrageenan-inspired hybrid graphene hydrogel as recyclable adsorbent for efficient scavenging of dyes and Hg^{2+} in water environment. *J. Colloid Interface Sci.* **2019**, *540*, 572–578. [CrossRef]
13. Schaider, L.A.; Rodgers, K.M.; Rudel, R.A. Review of organic wastewater compound concentrations and removal in onsite wastewater treatment systems. *Environ. Sci. Technol.* **2017**, *51*, 7304–7317. [CrossRef]
14. Hsien, C.; Low, J.S.C.; Chung, S.Y.; Tan, D.Z.L. Quality-based water and wastewater classification for waste-to-resource matching. *Resour. Conserv. Recycl.* **2019**, *151*, 104477. [CrossRef]
15. Salgot, M.; Folch, M. Wastewater treatment and water reuse. *Curr. Opin. Environ. Sci. Health* **2018**, *2*, 64–74. [CrossRef]
16. Sangamnere, R.; Misra, T.; Bherwani, H.; Kapley, A.; Kumar, R. A critical review of conventional and emerging wastewater treatment technologies. *Sustain. Water Resour. Manag.* **2023**, *9*, 58. [CrossRef]
17. Shamshad, J.; Ur Rehman, R. Innovative approaches to sustainable wastewater treatment: A comprehensive exploration of conventional and emerging technologies. *Environ. Sci. Adv.* **2024**, *4*, 189–222. [CrossRef]
18. Nishu; Kumar, S. Smart and innovative nanotechnology applications for water purification. *Hybrid Adv.* **2023**, *3*, 100044. [CrossRef]
19. Omer, S.N.; Saravanan, P.; Rajeshkannan, R.; Venkatkumar, S. A comprehensive review on nanotechnology and wastewater treatment: A synergistic approach to pollution control. *Sustain. Chem. One World* **2025**, *7*, 100082. [CrossRef]
20. Zekić, E.; Vuković, Ž.; Halkijević, I. Application of nanotechnology in wastewater treatment. *Gradevinar* **2018**, *70*, 315–323. [CrossRef]

21. Zahmatkesh, S.; Hajiaghaei-Keshteli, M.; Bokhari, A.; Sundaramurthy, S.; Panneerselvam, B.; Rezakhani, Y. Wastewater treatment with nanomaterials for the future: A state-of-the-art review. *Environ. Res.* **2023**, *216*, 114652. [CrossRef]
22. Saravanan, A.; Kumar, P.S.; Hemavathy, R.V.; Jeevanantham, S.; Jawahar, M.J.; Neshaanthini, J.P.; Saravanan, R. A review on synthesis methods and recent applications of nanomaterial in wastewater treatment: Challenges and future perspectives. *Chemosphere* **2022**, *307*, 135713. [CrossRef]
23. Sajid, M. Nanomaterials: Types, properties, recent advances, and toxicity concerns. *Curr. Opin. Environ. Sci. Health* **2022**, *25*, 100319. [CrossRef]
24. Sohail, A. Progress in nanomaterials: Synthesis, characterization, and applications. *Next Nanotechnol.* **2025**, *8*, 100263. [CrossRef]
25. Nain, A.; Sangili, A.; Hu, S.-R.; Chen, C.-H.; Chen, Y.-L.; Chang, H.-T. Recent progress in nanomaterial-functionalized membranes for removal of pollutants. *iScience* **2022**, *25*, 104616. [CrossRef]
26. Nyabadza, A.; Makhesana, M.; Plouze, A.; Kumar, A.; Ramirez, I.; Krishnamurthy, S.; Vazquez, M.; Brabazon, D. Advanced nanomaterials and dendrimers in water treatment and the recycling of nanomaterials: A review. *J. Environ. Chem. Eng.* **2024**, *12*, 112643. [CrossRef]
27. Gołub, A.; Piekutin, J. Removal of inorganic impurities from wastewater after production of soda ash on selected sorbents. *Sci. Rep.* **2020**, *10*, 4624. [CrossRef]
28. Yang, J.; Hou, B.; Wang, J.; Tian, B.; Bi, J.; Wang, N.; Li, X.; Huang, X. Nanomaterials for the removal of heavy metals from wastewater. *Nanomaterials* **2019**, *9*, 424. [CrossRef]
29. Kegl, T.; Košak, A.; Lobnik, A.; Novak, Z.; Kralj, A.K.; Ban, I. Adsorption of rare earth metals from wastewater by nanomaterials: A review. *J. Hazard. Mater.* **2020**, *386*, 121632. [CrossRef]
30. Zamel, D.; Khan, A.U.; Waris, A.; Ebrahim, A.; Abd El-Sattar, N.E.A. Nanomaterials advancements for enhanced contaminant removal in wastewater Treatment: Nanoparticles, Nanofibers, and Metal-Organic frameworks (MOFs). *Results Chem.* **2023**, *6*, 101092. [CrossRef]
31. Makhesana, M.A.; Patel, K.M.; Nyabadza, A. Applicability of nanomaterials in water and waste-water treatment: A state-of-the-art review and future perspectives. *Mater. Today Proc.* **2026**, *124*, 76–82. [CrossRef]
32. Awual, M.R.; Alharthi, N.H.; Hasan, M.M.; Karim, M.R.; Islam, A.; Znad, H.; Hossain, M.A.; Halim, M.E.; Rahman, M.M.; Khaleque, M.A. Inorganic-organic based novel nano-conjugate material for effective cobalt(II) ions capturing from wastewater. *Chem. Eng. J.* **2017**, *324*, 130–139. [CrossRef]
33. María, M.-C.; Marta, L.-G.; José, L.B.; Roberto, H.; Manuel, E. Green synthesis of iron oxide nanoparticles. Development of magnetic hybrid materials for efficient As(V) removal. *Chem. Eng. J.* **2016**, *301*, 83–91. [CrossRef]
34. Lunge, S.; Singh, S.; Sinha, A. Magnetic iron oxide (Fe_3O_4) nanoparticles from tea waste for arsenic removal. *J. Magn. Magn. Mater.* **2014**, *356*, 21–31. [CrossRef]
35. Xu, Q.; Li, W.; Ma, L.; Cao, D.; Owens, G.; Chen, Z. Simultaneous removal of ammonia and phosphate using green synthesized iron oxide nanoparticles dispersed onto zeolite. *Sci. Total Environ.* **2020**, *703*, 135002. [CrossRef]
36. Sharma, S.; Bassi, A.; Sanchita; Hasan, I. Photocatalytic nanostructured materials for heavy metal remediation: Mechanisms, challenges, and future prospects. *Mater. Sci. Semicond. Process.* **2026**, *204*, 110269. [CrossRef]
37. Le, Z.; Xue, J.; Wang, B.; Zhu, Y.A.; Wu, Z.; Nie, Y.; Xie, Z. MIL-100(Fe)/g-C_3N_4 composites with enhanced photocatalytic activity for UO_2^{2+} reduction under visible light. *Photochem. Photobiol. Sci.* **2023**, *22*, 59–71. [CrossRef]
38. Behera, A.; Mansingh, S.; Das, K.K.; Parida, K. Synergistic $ZnFe_2O_4$-carbon allotropes nanocomposite photocatalyst for norfloxacin degradation and Cr (VI) reduction. *J. Colloid Interface Sci.* **2019**, *544*, 96–111. [CrossRef]
39. Zhang, Y.; Zhang, Y.; Huang, Y.; Chen, X.; Cui, H.; Wang, M. Enhanced photocatalytic reaction and mechanism for treating cyanide-containing wastewater by silicon-based nano-titania. *Hydrometallurgy* **2020**, *198*, 105512. [CrossRef]
40. Khazaei, M.; Nasseri, S.; Ganjali, M.R.; Khoobi, M.; Nabizadeh, R.; Mahvi, A.H.; Nazmara, S.; Gholibegloo, E. Response surface modeling of lead (II) removal by graphene oxide-Fe_3O_4 nanocomposite using central composite design. *J. Environ. Health Sci. Eng.* **2016**, *14*, 2. [CrossRef]
41. Ali, I.; Kuznetsova, T.S.; Burakov, A.E.; Burakova, I.V.; Pasko, T.V.; Dyachkova, T.P.; Mkrtchyan, E.S.; Babkin, A.V.; Tkachev, A.G.; Albishri, H.M.; et al. Polyaniline Modified CNTs and Graphene Nanocomposite for Removal of Lead and Zinc Metal Ions: Kinetics, Thermodynamics and Desorption Studies. *Molecules* **2022**, *27*, 5623. [CrossRef]
42. Shi, Z.; Xu, C.; Guan, H.; Li, L.; Fan, L.; Wang, Y.; Liu, L.; Meng, Q.; Zhang, R. Magnetic metal organic frameworks (MOFs) composite for removal of lead and malachite green in wastewater. *Colloids Surf. A Physicochem. Eng. Asp.* **2018**, *539*, 382–390. [CrossRef]
43. Ismail, U.M.; Onaizi, S.A.; Vohra, M.S. Aqueous Pb(II) Removal Using ZIF-60: Adsorption Studies, Response Surface Methodology and Machine Learning Predictions. *Nanomaterials* **2023**, *13*, 1402. [CrossRef]
44. Huo, J.-B.; Yu, G. Layered Double Hydroxides Derived from MIL-88A(Fe) as an Efficient Adsorbent for Enhanced Removal of Lead (II) from Water. *Int. J. Mol. Sci.* **2022**, *23*, 14556. [CrossRef]

45. Shahzad, A.; Aslibeiki, B.; Slimani, S.; Ghosh, S.; Vocciante, M.; Grotti, M.; Comite, A.; Peddis, D.; Sarkar, T. Magnetic nanocomposite for lead (II) removal from water. *Sci. Rep.* **2024**, *14*, 17674. [CrossRef]
46. Shahmaleki, A.A.; Motevassel, M.; Isari, A.A.; Anvaripour, B. An effective approach for the adsorptive removal of lead from an aqueous medium using nano Prosopis Cineraria leaf ash (NPCLA): Characterization, operational effects, and recyclability. *Model. Earth Syst. Environ.* **2020**, *6*, 139–149. [CrossRef]
47. Li, K.; Guo, D.; Lin, F.; Wei, Y.; Liu, W.; Kong, Y. Electrosorption of copper ions by poly(m-phenylenediamine)/reduced graphene oxide synthesized via a one-step in situ redox strategy. *Electrochim. Acta* **2015**, *166*, 47–53. [CrossRef]
48. Dou, J.; Gan, D.; Huang, Q.; Liu, M.; Chen, J.; Deng, F.; Zhu, X.; Wen, Y.; Zhang, X.; Wei, Y. Functionalization of carbon nanotubes with chitosan based on MALI multicomponent reaction for Cu2+ removal. *Int. J. Biol. Macromol.* **2019**, *136*, 476–485. [CrossRef]
49. Tan, T.L.; Somat, H.b.A.; Latif, M.A.b.M.; Rashid, S.A. One-pot solvothermal synthesis of Zr-based MOFs with enhanced adsorption capacity for Cu^{2+} ions removal. *J. Solid State Chem.* **2022**, *315*, 123429. [CrossRef]
50. Zhao, P.; Geng, T.; Zhao, Y.; Tian, Y.; Li, J.; Zhang, H.; Zhao, W. Removal of Cu(II) ions from aqueous solution by a magnetic multi-wall carbon nanotube adsorbent. *Chem. Eng. J. Adv.* **2021**, *8*, 100184. [CrossRef]
51. Mubarak, N.M.; Solangi, N.H.; Karri, R.R.; Tan, Y.H.; Shams, S.; Ruslan, K.N.; Mazari, S.A.; Khalid, M. Holistic Mechanism of Nanomaterials for Removal of Cd^{2+} from the Wastewater. *Water Air Soil Pollut.* **2024**, *235*, 251. [CrossRef]
52. Nthwane, Y.B.; Fouda-Mbanga, B.G.; Thwala, M.; Pillay, K. Removal of Cd^{2+} by N-CNS/ZnO nanocomposite from wastewater and reuse of Cd^{2+}-N-CNS/ZnO in blood fingerprint detection. *Results Chem.* **2022**, *4*, 100660. [CrossRef]
53. Rashed, M.N.; Arifien, A.S.A.; El-Dowy, F.A. Muscovite based polyaniline nanocomposite as effective adsorbent for removal of Cd^{2+} and Pb^{2+} ions from liquid waste. *Sci. Rep.* **2025**, *15*, 20234. [CrossRef]
54. Chizitere Emenike, E.; George Adeniyi, A.; Iwuozor, K.O.; Okorie, C.J.; Egbemhenghe, A.U.; Omuku, P.E.; Chidiebere Okwu, K.; Saliu, O.D. A critical review on the removal of mercury (Hg^{2+}) from aqueous solution using nanoadsorbents. *Environ. Nanotechnol. Monit. Manag.* **2023**, *20*, 100816. [CrossRef]
55. Fu, K.; Liu, X.; Yu, D.; Luo, J.; Wang, Z.; Crittenden, J.C. Highly Efficient and Selective Hg(II) Removal from Water Using Multilayered $Ti_3C_2O_x$ MXene via Adsorption Coupled with Catalytic Reduction Mechanism. *Environ. Sci. Technol.* **2020**, *54*, 16212–16220. [CrossRef]
56. Rani, L.; Srivastav, A.L.; Kaushal, J.; Nguyen, X.C. Recent advances in nanomaterial developments for efficient removal of Hg(II) from water. *Environ. Sci. Pollut. Res.* **2022**, *29*, 62851–62869. [CrossRef]
57. Jia, F.; Wang, Q.; Wu, J.; Li, Y.; Song, S. Two-Dimensional Molybdenum Disulfide as a Superb Adsorbent for Removing Hg2+ from Water. *ACS Sustain. Chem. Eng.* **2017**, *5*, 7410–7419. [CrossRef]
58. Ibikunle, P.D.; Elemile, O.O.; Ejigboye, P.O.; Bala, D.O.; Olawolu, A.P.; Adebayo, A.A.; Olajide, O.S. Removal of hexavalent chromium from contaminated synthetic groundwater via functionalized carbon nanomaterials modified with zinc and potassium. *Sci. Rep.* **2025**, *15*, 33823. [CrossRef]
59. Pyrzynska, K. Nanomaterials for Removal and Speciation of Chromium. *Materials* **2025**, *18*, 1485. [CrossRef]
60. Rahman, M.H.; Fegade, U.; Parvez, M.; Arifuzzaman, M. Adsorption of hazardous Cr(VI) on CoMnZnO nanomaterials: Experimental and statistical approach. *Sci. Rep.* **2026**, *16*, 18135. [CrossRef]
61. Jibin, K.P.; Augustine, S.; Velayudhan, P.; George, J.S.; Krishnageham Sidharthan, S.; Paulose, S.V.; Thomas, S. Unleashing the Power of Graphene-Based Nanomaterials for Chromium(VI) Ion Elimination from Water. *Crystals* **2023**, *13*, 1047. [CrossRef]
62. Rajput, M.K.; Hazarika, R.; Sarma, D. Removal of As(III)/As(V) from aqueous solution using newly developed thiosalicylic acid coated magnetite [TSA@Fe3O4] nanoparticles. *Environ. Sci. Pollut. Res.* **2023**, *30*, 23348–23362. [CrossRef]
63. Samuel, M.S.; Selvarajan, E.; Sarswat, A.; Muthukumar, H.; Jacob, J.M.; Mukesh, M.; Pugazhendhi, A. Nanomaterials as adsorbents for As(III) and As(V) removal from water: A review. *J. Hazard. Mater.* **2022**, *424*, 127572. [CrossRef]
64. Chen, C.; Liu, J.; Cao, H.; Li, Z.; Lu, J.; Zhang, W. Highly Efficient Elimination of As(V) and As(III) from Aqueous Media Utilizing Fe-Ti-Mn/Chitosan Composite Xerogel Beads. *Gels* **2026**, *12*, 112. [CrossRef]
65. Chinnakoti, P.; Kurdekar, A.D.; Rao, K.M.; Kamisetti, V. A review of the emerging role of engineered nanomaterials as nanoadsorbents in enhanced drinking water defluoridation. *Discov. Environ.* **2025**, *3*, 151. [CrossRef]
66. Anna Rose, W.; Chunming, S.; Wenjie, S. Adsorptive Removal of Fluoride from Water Using Nanomaterials of Ferrihydrite, Apatite, and Brucite: Batch and Column Studies. *Environ. Eng. Sci.* **2019**, *36*, 634–642. [CrossRef]
67. Arab, N.; Derakhshani, R.; Sayadi, M.H. Approaches for the Efficient Removal of Fluoride from Groundwater: A Comprehensive Review. *Toxics* **2024**, *12*, 306. [CrossRef]
68. Huang, L.; Wan, K.; Yan, J.; Wang, L.; Li, Q.; Chen, H.; Zhang, H.; Xiao, T. Nanomaterials in Water Applications: Adsorbing Materials for Fluoride Removal. *Nanomaterials* **2021**, *11*, 1866. [CrossRef]
69. Das, T.K.; Kaur, J.; Mukhopadhyay, R.; Bezbaruah, A.; Sanyal, D. Engineered nanomaterials for removal, recovery, and reuse of phosphorus: From water to fertilizer pathways. *Adv. Colloid Interface Sci.* **2025**, *346*, 103672. [CrossRef]
70. Verma, S.; Nadagouda, M.N. Graphene-Based Composites for Phosphate Removal. *ACS Omega* **2021**, *6*, 4119–4125. [CrossRef]

71. Guo, K.; Song, Z.; Tang, C. Remediation of PO_4^{3-} in Water Using Biodegradable Materials Embedded with Lanthanum Oxide Nanoparticles. *Water* **2022**, *14*, 1656. [CrossRef]
72. Kassem, A.H.; Ayoub, G.M.; Zayyat, R. Advances in nanomaterials for phosphates removal from water and wastewater: A review. *Nanotechnol. Environ. Eng.* **2022**, *7*, 609–634. [CrossRef]
73. Swamy, K.R.; Shyamala, G.; Gurugubelli, T.R.; Vivek, S.; Priya, V.; Thanappan, S. Role of ZnO and TiO_2 nanomaterials in the removal of toxic trace elements from contaminated water: A review. *J. Trace Elem. Miner.* **2026**, *18*, 100331. [CrossRef]
74. You, H.; Li, W.; Zhang, Y.; Meng, Z.; Shang, Z.; Feng, X.; Ma, Y.; Lu, J.; Li, M.; Niu, X. Enhanced removal of NO3-N from water using Fe-Al modified biochar: Behavior and mechanism. *Water Sci. Technol.* **2020**, *80*, 2003–2012. [CrossRef]
75. Wu, J.; Zhao, J.; Li, H.; Miao, L.; Hou, J.; Xing, B. Simultaneous Removal of Selenite and Selenate by Nanosized Zerovalent Iron in Anoxic Systems: The Overlooked Role of Selenite. *Environ. Sci. Technol.* **2021**, *55*, 6299–6308. [CrossRef]
76. Marjanović, V.M.; Božić, D.; Friedrich, B. Selenium Removal Using Nanomaterials and Biosorbents Functionalized with Metal Oxides: A Review. *Metals* **2026**, *16*, 490. [CrossRef]
77. Matoušková, L.; Parschova, H.; Fartak, J. Removal of Selenium from Aqueous Solutions Using Polymer/Hydrated Iron Oxide Composites. *Solvent Extr. Ion Exch.* **2025**, *43*, 195–211. [CrossRef]
78. Vijayakumar, G.; Thangavel, E.; Alshamsi, D.; Sherif, M.; Murad, A.A.; Sangaraju, S. A critical review on the prospective role of nanomaterials in the effectual removal of radionuclides from wastewater—State of the art and future challenges. *Environ. Technol. Innov.* **2025**, *38*, 104129. [CrossRef]
79. Li, Y.; Wang, S.; Wang, X. Highly selective removal of U(VI) from aqueous solutions by porous nanomaterials. *EcoEnergy* **2024**, *2*, 205–219. [CrossRef]
80. Esrafili, A.; Ghambarian, M.; Yousefi, M.; Yazdanfar, N. Efficient removal of uranium (VI) from environmental water samples by cyclodextrin-intercalated layered double hydroxide-coated magnetic nanoparticles. *Sci. Rep.* **2024**, *14*, 30974. [CrossRef]
81. Ma, J.; Wang, C.; Xi, W.; Zhao, Q.; Wang, S.; Qiu, M.; Wang, J.; Wang, X. Removal of Radionuclides from Aqueous Solution by Manganese Dioxide-Based Nanomaterials and Mechanism Research: A Review. *ACS ES&T Eng.* **2021**, *1*, 685–705. [CrossRef]
82. Thirunavukkarasu, A.; Nithya, R.; Sivashankar, R. A review on the role of nanomaterials in the removal of organic pollutants from wastewater. *Rev. Environ. Sci. Bio/Technol.* **2020**, *19*, 751–778. [CrossRef]
83. Anjum, M.; Miandad, R.; Waqas, M.; Gehany, F.; Barakat, M.A. Remediation of wastewater using various nano-materials. *Arab. J. Chem.* **2019**, *12*, 4897–4919. [CrossRef]
84. Chahar, M.; Khaturia, S.; Singh, H.L.; Solanki, V.S.; Agarwal, N.; Sahoo, D.K.; Yadav, V.K.; Patel, A. Recent advances in the effective removal of hazardous pollutants from wastewater by using nanomaterials—A review. *Front. Environ. Sci.* **2023**, *11*, 1226101. [CrossRef]
85. Singh, D.; Gurjar, B.R. Recent innovation and impacts of nano-based technologies for wastewater treatment on humans: A review. *Environ. Monit. Assess.* **2023**, *195*, 357. [CrossRef]
86. El-Fawal, E.M.; Younis, S.A.; Moustafa, Y.M.; Serp, P. Preparation of solar-enhanced AlZnO@carbon nano-substrates for remediation of textile wastewaters. *J. Environ. Sci.* **2020**, *92*, 52–68. [CrossRef]
87. Di, G.; Xue, X.; Tingting, J.; Hong, J.; Baohui, W.; Xirui, W. Solar multifield-driven hybrid chemical system for purification of organic wastewater focused on a nano-carbon/TiO_2/Ti central electrode. *Ind. Eng. Chem. Res.* **2020**, *59*, 11527–11536. [CrossRef]
88. Yang, G.; Li, Y.; Yang, S.; Liao, J.; Cai, X.; Gao, Q.; Fang, Y.; Peng, F.; Zhang, S. Surface oxidized nano-cobalt wrapped by nitrogen-doped carbon nanotubes for efficient purification of organic wastewater. *Sep. Purif. Technol.* **2021**, *259*, 118098. [CrossRef]
89. Yang, G.; Zhang, D.; Zhu, G.; Zhou, T.; Song, M.; Qu, L.; Xiong, K.; Li, H. A Sm-MOF/GO nanocomposite membrane for efficient organic dye removal from wastewater. *RSC Adv.* **2020**, *10*, 8540–8547. [CrossRef]
90. Isawi, H. Evaluating the performance of different nano-enhanced ultrafiltration membranes for the removal of organic pollutants from wastewater. *J. Water Process Eng.* **2019**, *31*, 100833. [CrossRef]
91. Liu, M.; Zhang, L.; Wang, M.; Wang, X.; Cui, H.; Wei, J.; Li, X. The role of metal-organic frameworks in removing emerging contaminants in wastewater. *J. Clean. Prod.* **2023**, *429*, 139526. [CrossRef]
92. Kaur, H.; Devi, N.; Siwal, S.S.; Alsanie, W.F.; Thakur, M.K.; Thakur, V.K. Metal–Organic Framework-Based Materials for Wastewater Treatment: Superior Adsorbent Materials for the Removal of Hazardous Pollutants. *ACS Omega* **2023**, *8*, 9004–9030. [CrossRef]
93. Jia, F.; Xiao, X.; Nashalian, A.; Shen, S.; Yang, L.; Han, Z.; Qu, H.; Wang, T.; Ye, Z.; Zhu, Z.; et al. Advances in graphene oxide membranes for water treatment. *Nano Res.* **2022**, *15*, 6636–6654. [CrossRef]
94. Vitiello, G.; Venezia, V.; Verrillo, M.; Nuzzo, A.; Houston, J.; Cimino, S.; D'Errico, G.; Aronne, A.; Paduano, L.; Piccolo, A.; et al. Hybrid humic acid/titanium dioxide nanomaterials as highly effective antimicrobial agents against gram(-) pathogens and antibiotic contaminants in wastewater. *Environ. Res.* **2021**, *193*, 110562. [CrossRef]
95. Yi, H.; Yan, M.; Huang, D.; Zeng, G.; Lai, C.; Li, M.; Huo, X.; Qin, L.; Liu, S.; Liu, X.; et al. Synergistic effect of artificial enzyme and 2D nano-structured Bi_2WO_6 for eco-friendly and efficient biomimetic photocatalysis. *Appl. Catal. B Environ.* **2019**, *250*, 52–62. [CrossRef]

96. Siong, V.L.E.; Tai, X.H.; Lee, K.M.; Juan, J.C.; Lai, C.W. Unveiling the enhanced photoelectrochemical and photocatalytic properties of reduced graphene oxide for photodegradation of methylene blue dye. *RSC Adv.* **2020**, *10*, 37905–37915. [CrossRef]
97. Huang, G.; Zhang, Y.; Zhang, R.; Zhang, M.; Zhang, L.; Xin, Y.; Liu, Y.; Chen, J. Removal of methyl orange and methylene blue by bimetallic zinc/cobalt metal–organic skeleton/carbon nanotubes (Zn/Co-ZIF@CNTs). *RSC Adv.* **2025**, *15*, 4681–4692. [CrossRef]
98. Patel, R.; Mahabari, K.; Patel, K.; Patel, M.; Jadhav, A.H.; Dharaskar, S.; Karri, R.R.; Chaudhari, N. MoS2/MXene composite material for high-performance removal of Rhodamine B dye: Synthesis and application. *Sci. Rep.* **2025**, *15*, 42099. [CrossRef]
99. Kayani, K.F. Bimetallic metal–organic frameworks (BMOFs) for dye removal: A review. *RSC Adv.* **2024**, *14*, 31777–31796. [CrossRef]
100. Munawar, Z.; Ghazanfar, S.; Asif, H.M.; Khan, M.A.; Sirajuddin, M.; Tariq, M.; Shirazi, J.H.; Haider, A. Synthesis, characterization of ternary metal oxides nanocomposite (ZnO–CdO–Pr_2O_3) for photodegradation of organic pollutants: Methylene blue & rhodamine B. *J. Iran. Chem. Soc.* **2023**, *20*, 2245–2256. [CrossRef]
101. Farahmandzadeh, F.; Molaei, M.; Salehi, S.; Molahosseini, E. Simultaneous and fast degradation of methylene blue, methylene orange, and Rhodamine B dyes by high-performance rGO/Fe3O4/ZnSe magnetic nanocomposites. *Colloids Surf. A Physicochem. Eng. Asp.* **2024**, *685*, 133229. [CrossRef]
102. Ha, H.Q.; Nguyen, N.P.T.; Nguyen, T.T.T.; Tran, T.V. Removal of selected antibiotics and anti-inflammatory drugs using metal–organic framework-based adsorbents. *J. Ind. Eng. Chem.* **2026**, *156*, 60–77. [CrossRef]
103. Yin, H.; Guo, S.; Liao, W.; Liu, M.; Qin, H.; Zhang, Q.; Xiong, X.; Li, Z.; Chen, P.; Zhu, S. Interface functions of nanomaterials in AOPs for antibiotic removal: Mechanisms and environmental implications. *Environ. Surf. Interfaces* **2026**, *4*, 249–273. [CrossRef]
104. Yang, M.; He, J.; He, J.; Cao, J. Removal of tetracycline and ciprofloxacin from aqueous solutions using magnetic copper ferrite nanoparticles. *J. Sci. Adv. Mater. Devices* **2024**, *9*, 100717. [CrossRef]
105. Aziz, K.; Raza, N.; Kanwal, N.; Khairy, M.; Ahmadi, Y.; Kim, K.-H. Recent advances in nanomaterial-based adsorbents for removal of pharmaceutical pollutants from wastewater. *Mater. Horiz.* **2025**, *12*, 6043–6068. [CrossRef]
106. Doolabi, S.D.; Shamspur, T.; Mostafavi, A.; Mohamadi, M. Efficient removal of tetracycline from aqueous media using a novel Zr-MOF/CuCo2O4 nanocomposite: Synthesis, characterization, and mechanistic insights. *Sci. Rep.* **2026**, *16*, 22773. [CrossRef]
107. Bagri, F.; Hassani, A.; Jarrah, A.; Parnianchi, F. Highly effective elimination of tetracycline and ciprofloxacin antibiotics from synthetic wastewater by novel magnetic $P_2W_{18}O_{62}$/MIL-101 (Fe)/$NiFe_2O_4$ nanocomposite. *Sep. Purif. Technol.* **2024**, *329*, 125128. [CrossRef]
108. Shamim, A.; Neelam, K.; Kamaal, S.; Ali, A.; Ahmad, M. Removal of pesticide pollutants from aqueous waste utilizing nanomaterials via photocatalytic process: A review. *Int. J. Environ. Sci. Technol.* **2024**, *21*, 4653–4684. [CrossRef]
109. Gacem, M.A.; Telli, A.; Ould El Hadj Khelil, A. Chapter 15—Nanomaterials for detection, degradation, and adsorption of pesticides from water and wastewater. In *Aquananotechnology*; Abd-Elsalam, K.A., Zahid, M., Eds.; Elsevier: Amsterdam, Netherlands, 2021; pp. 325–346.
110. Roy, A.; Roy, M.; Alghamdi, S.; Dablool, A.S.; Almakki, A.A.; Ali, I.H.; Yadav, K.K.; Islam, M.R.; Cabral-Pinto, M.M.S. Role of Microbes and Nanomaterials in the Removal of Pesticides from Wastewater. *Int. J. Photoenergy* **2022**, *2022*, 2131583. [CrossRef]
111. Zhou, S.; Guo, J.; Zou, Y.; Wang, L.; Kaw, H.Y.; Quinto, M.; Meng, L.-Y.; Dong, M. Fast removal of phenolic compounds from water using hierarchical porous carbon nanofibers membrane. *J. Chromatogr. A* **2022**, *1685*, 463624. [CrossRef]
112. Razavi, L.; Raissi, H.; Hashemzehi, O.; Farzad, F. Significantly enhanced performance for phenol compounds removal by MOF-5 nano-composite via its surface modification. *npj Clean Water* **2024**, *7*, 44. [CrossRef]
113. Ramírez-Hernández, M.; Cox, J.; Thomas, B.; Asefa, T. Nanomaterials for Removal of Phenolic Derivatives from Water Systems: Progress and Future Outlooks. *Molecules* **2023**, *28*, 6568. [CrossRef]
114. Sajid, M.; Suliman, M.A.; Nazal, M.K.; Ihsanullah, I.; Rehman, N.U. State-of-the-art adsorbent materials for Bisphenol A removal from water: A systematic evaluation of mechanisms, performance, and environmental sustainability. *J. Water Process Eng.* **2026**, *87*, 110067. [CrossRef]
115. Alkhair, S.; Zouari, N.; Ibrahim Ahmad Ibrahim, M.; Al-Ghouti, M.A. Efficacy of adsorption processes employing green nanoparticles for bisphenol A decontamination in water: A review. *Environ. Nanotechnol. Monit. Manag.* **2024**, *22*, 100963. [CrossRef]
116. Liu, S.; Jassby, D.; Mandler, D.; Schäfer, A.I. Differentiation of adsorption and degradation in steroid hormone micropollutants removal using electrochemical carbon nanotube membrane. *Nat. Commun.* **2024**, *15*, 9524. [CrossRef]
117. Nguyen, M.N.; Weidler, P.G.; Schwaiger, R.; Schäfer, A.I. Interactions between carbon-based nanoparticles and steroid hormone micropollutants in water. *J. Hazard. Mater.* **2021**, *402*, 122929. [CrossRef]
118. Minhas, S.; Pandey, R.P.; Hasan, S.W. Emerging nanomaterials incorporated in membranes for polyfluoroalkyl substances (PFAS) removal from water: A review. *J. Environ. Manag.* **2025**, *373*, 123888. [CrossRef]
119. Hussain, H.N.; Jilani, M.I.; Imtiaz, F.; Ahmed, T.; Arshad, M.B.; Mudassar, M.; Sharif, M.N. Advances in the removal of Polyfluoroalkyl Substances (PFAS) from water using destructive and non-destructive methods. *Green Anal. Chem.* **2025**, *12*, 100225. [CrossRef]

120. Lee, D.; Jun, B.-M.; Park, J.; Jang, M.; Lee, S.; Snyder, S.A.; Park, C.M.; Yoon, Y. A review of removal of per- and polyfluoroalkyl substances using metal–organic framework-based nanoadsorbents. *Nano Converg.* **2025**, *12*, 56. [CrossRef]
121. Salehpour, N.; Mahdavi, P.; Nojavan, S. Advancements in nanomaterials for water and wastewater treatment and monitoring. *Trends Environ. Anal. Chem.* **2026**, *49*, e00299. [CrossRef]
122. Cheriyamundath, S.; Vavilala, S.L. Nanotechnology-based wastewater treatment. *Water Environ. J.* **2021**, *35*, 123–132. [CrossRef]
123. Zhang, X.; Lian, G.; Zhang, S.; Cui, D.; Wang, Q. Boron nitride nanocarpets: Controllable synthesis and their adsorption performance to organic pollutants. *CrystEngComm* **2012**, *14*, 4670–4676. [CrossRef]
124. Pandey, R.P.; Kallem, P.; Hegab, H.M.; Rasheed, P.A.; Banat, F.; Hasan, S.W. Cross-linked laminar graphene oxide membranes for wastewater treatment and desalination: A review. *J. Environ. Manag.* **2022**, *317*, 115367. [CrossRef]
125. Shah, I.A.; Bilal, M.; Ihsanullah, I.; Ali, S.; Yaqub, M. Revolutionizing water purification: Unleashing graphene oxide (GO) membranes. *J. Environ. Chem. Eng.* **2023**, *11*, 111450. [CrossRef]
126. Muhammad, P.; Zada, A.; Rashid, J.; Hanif, S.; Gao, Y.; Li, C.; Li, Y.; Fan, K.; Wang, Y. Defect Engineering in Nanocatalysts: From Design and Synthesis to Applications. *Adv. Funct. Mater.* **2024**, *34*, 2314686. [CrossRef]
127. Panjwani, M.K.; Ahmadzai, S.M.; Li, J.; Luo, Z.; Eshaq, G.; Xiao, K.; Zeng, H. Heteroatom doping strategies in single-atom catalysts: Tuning electronic structure for selective peroxymonosulfate activation. *J. Mater. Chem. A* **2026**, *14*, 12509–12539. [CrossRef]
128. Guo, M.; Zhang, S.; Ran, J.; Qiao, S.-Z. Vacancy-interface coupling in nanomaterials for photocatalytic energy and environmental applications. *Chem* **2026**, *12*, 102913. [CrossRef]
129. Samarasinghe, L.V.; Muthukumaran, S.; Baskaran, K. Heterojunction photocatalysts for solar-driven wastewater treatment: Interfacial design, charge carrier dynamics, and advanced characterization techniques. *J. Water Process Eng.* **2025**, *79*, 108960. [CrossRef]
130. Shabbir, A.; Sardar, S.; Mumtaz, A. Mechanistic investigations of emerging type-II, Z-scheme and S-scheme heterojunctions for photocatalytic applications—A review. *J. Alloys Compd.* **2024**, *1003*, 175683. [CrossRef]
131. Du, W.; Wang, X.; Li, H.; Ma, D.; Hou, S.; Zhang, J.; Qian, X.; Pang, H. ZrO_2/Dy_2O_3 solid solution nano-materials: Tunable composition, visible light–responsive photocatalytic activities and reaction mechanism. *J. Am. Ceram. Soc.* **2013**, *96*, 2979–2986. [CrossRef]
132. Du, W.; Zhu, Z.; Zhang, X.; Wang, D.; Liu, D.; Qian, X.; Du, J. RE/ZrO_2 (RE = Sm, Eu) composite oxide nano-materials: Synthesis and applications in photocatalysis. *Mater. Res. Bull.* **2013**, *48*, 3735–3742. [CrossRef]
133. Wu, C.; Tu, J.; Tian, C.; Geng, J.; Lin, Z.; Dang, Z. Defective magnesium ferrite nano-platelets for the adsorption of As(V): The role of surface hydroxyl groups. *Environ. Pollut.* **2018**, *235*, 11–19. [CrossRef]
134. Aggelopoulos, C.A.; Dimitropoulos, M.; Govatsi, A.; Sygellou, L.; Tsakiroglou, C.D.; Yannopoulos, S.N. Influence of the surface-to-bulk defects ratio of ZnO and TiO_2 on their UV-mediated photocatalytic activity. *Appl. Catal. B Environ.* **2017**, *205*, 292–301. [CrossRef]
135. Liu, H.; Ma, H.T.; Li, X.Z.; Li, W.Z.; Wu, M.; Bao, X.H. The enhancement of TiO_2 photocatalytic activity by hydrogen thermal treatment. *Chemosphere* **2003**, *50*, 39–46. [CrossRef]
136. Fang, J.; Fan, H.; Ma, Y.; Wang, Z.; Chang, Q. Surface defects control for ZnO nanorods synthesized by quenching and their anti-recombination in photocatalysis. *Appl. Surf. Sci.* **2015**, *332*, 47–54. [CrossRef]
137. Liu, H.; Long, L.; Weng, X.; Zheng, S.; Xu, Z. Efficient removal of tetrabromobisphenol A using microporous and mesoporous carbons: The role of pore structure. *Microporous Mesoporous Mater.* **2020**, *298*, 110052. [CrossRef]
138. Thommes, M.; Kaneko, K.; Neimark, A.V.; Olivier, J.P.; Rodriguez-Reinoso, F.; Rouquerol, J.; Sing, K.S.W. Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report). *Pure Appl. Chem.* **2015**, *87*, 1051–1069. [CrossRef]
139. Tao, S.; Zhu, Z.; Meng, C.; Wang, C. Preparation and morphology control of magnetic mesoporous silica via metalorganic amphiphiles self-assembly. *Microporous Mesoporous Mater.* **2013**, *171*, 94–102. [CrossRef]
140. Mitome, T.; Hirota, Y.; Uchida, Y.; Nishiyama, N. Porous structure and pore size control of mesoporous carbons using a combination of a soft-templating method and a solvent evaporation technique. *Colloids Surf. A Physicochem. Eng. Asp.* **2016**, *494*, 180–185. [CrossRef]
141. Wu, X.; Su, R.; Pei, B.; Zhu, Y.; Huang, Z. Pore structure control of porous carbon via the synergistic effect of boric acid and divalent metal iron salt. *Mater. Lett.* **2019**, *255*, 126539. [CrossRef]
142. Cui, Y.; Qin, L.; Kang, W.; Ma, J.; Yang, Y.; Liu, X. Magnetic carbon nanospheres: Synthesis, characterization, and adsorbability towards quinoline from coking wastewater. *Chem. Eng. J.* **2020**, *382*, 122995. [CrossRef]
143. Li, Y.; Zheng, X.; Yan, Z.; Tian, D.; Ma, J.; Zhang, X.; Jiang, L. Closed pore structured $NiCo_2O_4$-coated nickel foams for stable and effective oil/water separation. *ACS Appl. Mater. Interfaces* **2017**, *9*, 29177–29184. [CrossRef]
144. Barakan, S.; Aghazadeh, V. Structural modification of nano bentonite by aluminum, iron pillarization and 3D growth of silica mesoporous framework for arsenic removal from gold mine wastewater. *J. Hazard. Mater.* **2019**, *378*, 120779. [CrossRef]

145. Ji, D.; Xiao, C.; An, S.; Zhao, J.; Hao, J.; Chen, K. Preparation of high-flux PSF/GO loose nanofiltration hollow fiber membranes with dense-loose structure for treating textile wastewater. *Chem. Eng. J.* **2019**, *363*, 33–42. [CrossRef]
146. Ushakov, N.M.; Vasil'kov, M.Y.; Shaturnuy, V.R. Influence of the pore structure on the electron barrier height of metal-ceramic nanomaterials based on gold-anodic aluminum oxide. *Semiconductors* **2018**, *52*, 2078–2080. [CrossRef]
147. Ji, Z.; Wang, H.; Canossa, S.; Wuttke, S.; Yaghi, O.M. Pore chemistry of metal–organic frameworks. *Adv. Funct. Mater.* **2020**, *30*, 2000238. [CrossRef]
148. Pal, N.; Lee, J.-H.; Cho, E.-B. Recent Trends in Morphology-Controlled Synthesis and Application of Mesoporous Silica Nanoparticles. *Nanomaterials* **2020**, *10*, 2122. [CrossRef]
149. El-Toni, A.M.; Habila, M.A.; Labis, J.P.; Alothman, Z.A.; Alhoshan, M.; Elzatahry, A.A.; Zhang, F. Design, synthesis and applications of core–shell, hollow core, and nanorattle multifunctional nanostructures. *Nanoscale* **2016**, *8*, 2510–2531. [CrossRef]
150. Guo, Y.; Xu, K.; Wu, C.; Zhao, J.; Xie, Y. Surface chemical-modification for engineering the intrinsic physical properties of inorganic two-dimensional nanomaterials. *Chem. Soc. Rev.* **2015**, *44*, 637–646. [CrossRef]
151. Zheng, Z.; Cox, M.; Li, B. Surface modification of hexagonal boron nitride nanomaterials: A review. *J. Mater. Sci.* **2018**, *53*, 66–99. [CrossRef]
152. Cai, Z.; Sun, Y.; Liu, W.; Pan, F.; Sun, P.; Fu, J. An overview of nanomaterials applied for removing dyes from wastewater. *Environ. Sci. Pollut. Res.* **2017**, *24*, 15882–15904. [CrossRef]
153. Zhang, Y.-R.; Wang, S.-Q.; Shen, S.-L.; Zhao, B.-X. A novel water treatment magnetic nanomaterial for removal of anionic and cationic dyes under severe condition. *Chem. Eng. J.* **2013**, *233*, 258–264. [CrossRef]
154. Ghomashi, P.; Charkhi, A.; Kazemeini, M.; Yousefi, T. Removal of fluoride from wastewater by natural and modified nano clinoptilolite zeolite. *J. Water Environ. Nanotechnol.* **2020**, *5*, 270–282. [CrossRef]
155. Sadati Behbahani, N.; Rostamizadeh, K.; Yaftian, M.R.; Zamani, A.; Ahmadi, H. Covalently modified magnetite nanoparticles with PEG: Preparation and characterization as nano-adsorbent for removal of lead from wastewater. *J. Environ. Health Sci. Eng.* **2014**, *12*, 103. [CrossRef]
156. Mazari, S.A.; Ali, E.; Abro, R.; Khan, F.S.A.; Ahmed, I.; Ahmed, M.; Nizamuddin, S.; Siddiqui, T.H.; Hossain, N.; Mubarak, N.M.; et al. Nanomaterials: Applications, waste-handling, environmental toxicities, and future challenges—A review. *J. Environ. Chem. Eng.* **2021**, *9*, 105028. [CrossRef]
157. Joudeh, N.; Linke, D. Nanoparticle classification, physicochemical properties, characterization, and applications: A comprehensive review for biologists. *J. Nanobiotechnology* **2022**, *20*, 262. [CrossRef]
158. Liu, S.; Guo, H.; Kong, Z.; Han, X.; Gao, Y.; Zhang, Y.; Daigger, G.T.; Zhang, P.; Kang, J.; Yu, S.; et al. Performance improvement and application of copper-based nanomaterials in membrane technology for water treatment: A review. *J. Environ. Manag.* **2024**, *370*, 122755. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.