Sustainable nanotechnology based wastewater treatment strategies: achievements, challenges and future perspectives

Shakeel Ahmad Bhat[1], Farooq Sher[2,*], Mariam Hameed[3,4], Omar Bashir[5], Rohitashw Kumar[1], Dai-Viet N. Vo[6], Parvaiz Ahmad[7], Eder C. Lima[8]

[1]*College of Agricultural Engineering, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Jammu and Kashmir, India*

[2] *Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, United Kingdom*

[3]*School of Chemistry, University of the Punjab, Lahore 54590, Pakistan*

[4]*International Society of Engineering Science and Technology, United Kingdom*

[5]*Department of Food Technology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Jammu and Kashmir, India*

[6]*Center of Excellence for Green Energy and Environmental Nanomaterials (CE@GrEEN), Nguyen Tat Thanh University, 300A Nguyen Tat Thanh, District 4, Ho Chi Minh City 755414, Vietnam*

[7]*Botany and Microbiology Department, College of Science, King Saud University, P. O. Box. 2460, Riyadh 11451, Saudi Arabia*

[8]*Institute of Chemistry, Federal University of Rio Grande do Sul (UFRGS), Av. Bento Goncalves 9500, P.O. Box 15003, ZIP 91501-970, Porto Alegre, RS, Brazil*

***Corresponding author:**
Dr. F. Sher
Assistant Professor
Department of Engineering, School of Science and Technology
Nottingham Trent University
Nottingham
NG11 8NS
UK
E-mail address: Farooq.Sher@ntu.ac.uk (F. Sher)
Tel.: +44 (0) 115 84 86679

Abstract

Nanotechnology being an emerging science for water treatment requires more research emphasis and depth knowledge. For wastewater treatment, different forms of nanomaterials are used based on the type of contaminants and treatment efficiency desired. With the development in the field of nanomaterials, novel and emerging nanomaterials are coming into existence. The nanomaterials used for wastewater treatment can be carbon, single-walled carbon nanotubes, multiple walled carbon nanotubes, covalent organic frameworks, metal and metal oxides based nanoparticles. Graphene based nanoparticles, their oxides (GO) and reduced graphene oxide (rGO) find tremendous applicability to be used in wastewater treatment purposes. Due to the introduction of graphene oxide nanoparticles in the adsorbent materials, their adsorption capacities have considerably risen and such materials have also improved the mechanical stability of the adsorbent. Ferric oxide shows greater adsorption capacity for organic pollutants. Furthermore, magnetic nano-powder confers a low adsorption capacity for phenols. Pyrrolidone reduced graphene oxide (PVP-RGO) nanoparticles have been used as adsorbents for the elimination of inorganic target contaminant Copper, with great adsorption (1698 mg/g). The present study comprehensively reviews nanotechnology as a wastewater treatment method besides enlightening its safety issues and efficiency. The novelty of this article is that it highlights the overview of various types of nanomaterials based on recent research works in the last decades. Such an approach will be helpful to get insights into technological advances, applications and future challenges of nanotechnology implementation for wastewater treatment.

Keywords: Environmental pollution; Nanotechnology; Covalent organic frameworks; Metal nanomaterials; carbon footprints and Wastewater treatment.

1 Introduction

Water is one of the most essential and critical resources of human society for all lives on earth (Morrison, Shields et al. 2020, Rubilar, Hubbard et al. 2020). The increasing necessity of water and mounting water pollution are major issues of water management (Elbeltagi, Azad et al. 2021). Earth is the only habitable planet in the solar system with around 70% of its surface covered by water (Pradeep 2009). However, only 2.5% of the water present on the earth is fresh and the rest is saline (Oki and Kanae 2006). Of the total freshwater present, only a small percentage is present as surface water in the river, lake, etc. as freshwater. Hence, surface water is an indispensable resource for human kind (Bhat, Pandit et al. 2017). Today, the availability of safe potable water has become a global problem because of substantial water pollution (Acharya, Blackburn et al. 2020, Ponce-Rodríguez, Verdú-Andrés et al. 2020). Various anthropogenic activities lead to the contamination of fresh water thereby, leaving it unfit for use in domestic and other agricultural uses. Nature journal highlights on its website that "things in the world are getting worse and more than one trillion people lack access to clean water" in relation to the potential global water crisis (Jiang, Carrijo et al. 2019, Edokpayi, Makungo et al. 2020).

The industrialization and disposal of electronic wastes further complicate the problem. Several environmentally degrading substances and toxic metals such as lead, mercury, arsenic, cobalt, nickel, etc. end up in water bodies (Yadav, Chowdhary et al. 2017). Additionally, at low concentrations, emergent pollutants can be harmful to habitats and human health (Basheer 2018). There are several conventional methods (coagulation-flocculation, electrochemical treatment, adsorption, ion-exchange, chemical precipitation and membrane filtration) in addition to advanced methods (ultrafiltration, adsorption, chemical precipitation, biological oxidation, coagulation, micro screening and biosensor) for the treatment of contaminated water (Shah, Dar et al. 2020). However, conventional techniques prove inefficient for water treatment besides being expensive. Industrial wastewater usually is known to contain toxic heavy metals (Liu, Zhu et al. 2020, Wu, Shi et al. 2020). Therefore, the treatment of wastewater requires adoption of a technology that is cost-effective and requires low energy.

Nanotechnology has emerged as a novel technology to address the problem of water scarcity and wastewater treatment. The multifunctional and highly effective nanotechnology-enabled wastewater treatment provides new treatment capabilities that could allow the commercial use of unconventional water sources to increase water supply. (Olvera, Silva et al. 2017, Wong, Tan et al. 2019, Deshpande, Agrawal et al. 2020). Nanomaterials remove hazardous metals from water and thus play a significant role in wastewater treatment (Deshpande, Agrawal et al. 2020). The past few decades have seen a remarked advancement in the field of nanotechnology that has encouraged researchers to explore new research areas. The unique properties of nanostructured materials could provide more sustainable solutions to existing wastewater management problems (Lu, Wang et al. 2016). Nanomaterials, due to their distinctive characteristics such as greater aspect ratio, electrostatic properties, tunable pore volume, reactivity, hydrophobic and hydrophilic reaction have several unique properties (Das, Ali et al. 2014).

Nanotechnology-based waste-water treatment techniques present significant challenges to the current techniques. The current technologies are efficient to a great extent for pollutant removal from wastewaters, although they are time-consuming and cost-intensive. Nanotechnology solves several environmental problems and helps to reduce labour, time and investment demanded by the wastewater treatment industry (Kanchi 2014). The advantages and significance of nanotechnology include; it plays a vital role in the manufacturing of new materials, transform energy into various ways as energy storage and generation like solar power devices, take part in Phyto-toxicity, for environmental pollution control following green synthesis of nanomaterial with low cost, High surface area, greater adsorption capacity chemically stable, easily activated by light and degraded the pollutant from wastewater and gives better result to improves the antimicrobial activity(Cheriyamundath, Vavilala et al. 2021). Moreover, various limitations associated with conventional water treatment methods are given in Table 1.

Table 1. Conventional water treatment methods and associated limitations.

Conventional methods	**Limitations**
Distillation	- Majority of the contaminants remain behind
	- Inefficient for pollutants with high boiling points (>100 °C)
Coagulation and flocculation	- Less accurate method
	- Needs the addition of alkaline additives for lowering pH
Chemical transformation	- Excess reagents are required
Ultraviolet irradiation	- Inefficient for heavy metals removal
	- Expensive method
Biological treatment	- Difficult control over microorganisms
	- Expensive
	- Time-consuming
Reverse osmosis	- Energy-intensive
	- Inefficient for volatile organics and pharmaceuticals
	- Acidic nature of treated water
Carbonfilter	- Susceptible to mould
	- Frequent changing of filters
	- Clogging
Ultrafiltration	- Susceptible to particulate plugging
	- Inefficient for dissolved inorganics

Microfiltration	- Regular cleaning, less sensitive to microbes esp. viruses, - Inefficient for fluorides, nitrates, metals, etc.
Nanofiltration	- Membrane fouling - High energy - Pretreatment requirement

Generally, nanomaterials are classified as materials smaller than 100 nm in at least one dimension (Chhabra and Kumar 2020). Nanomaterials can transform their structures into specific functionalities, making them more promising for wastewater treatment (Karthigadevi, Manikandan et al. 2021). The small size of nanomaterials gives rise to several unique properties specific to nanomaterials as compared to bulk materials. The high surface area to volume ratio of these nano based materials gives rise to more surface dependent properties. Nanomaterials have proven to be quite effective in the removal of several contaminants due to their excellent adsorbent properties and beneficial physicochemical properties (Das, Ali et al. 2014). Nanotechnology is being explored as a promising technology and has demonstrated remarkable accomplishments in various fields including wastewater treatment. Nanostructures offer unparalleled opportunities to make more effective catalysts and redox active media for wastewater purification, owing to their small size, large surface area, and ease of functionalization. Nanomaterials are effective in the elimination of several pollutants from wastewater such as heavy metals, organic and inorganic solvents, color as well as biological toxins, and pathogens that cause diseases like cholera and typhoid.

The multifunctional and highly effective nanotechnology-enabled wastewater treatment offers a new treatment capacity that could allow the commercial use of unconventional water sources to increase water supply. Nanotechnology-based wastewater treatment is a trending topic and is attracting researchers from various fields. The number of published works related to this field has shown a spike by growing from a merely 5% in 2005 to more than 80% by 2019. Currently, the application of nano-based multi-dimensional covalent organic framework (COF) has proved to be a promising material for capturing various types of pollutants from aqueous solutions (Liu, Pang et al. 2021). Further, Graphitic carbon nitride as a metal-free and emerging material finds tremendous applications to be used as an effective heavy metal scavenger from aqueous phases (Hu, Wang et al. 2021). The material has high chemical and thermal stability besides being low cost and eco-friendly in nature. The development of novel materials with highly efficient and excellent selectivity for capturing U(VI) from nuclear-related wastewater and seawater is highly desirable The recent advances of perovskite-based photocatalysts in environmental clean up were comprehensively highlighted by Wang et al., (Wang, Zhang et al. 2021), which are crucial for the application of perovskite-based photocatalysts for highly efficient removal of various environmental pollutants in environmental remediation The expertise in the field of nanotechnology offers great potential for continuous improvement in environmental quality and water conservation.

Therefore, this review highlights nanotechnology-based wastewater treatment methods being developed for physicochemical as well as bio-decontamination of water i.e., bio-sorption and nano-adsorption of contaminants using various types of carbon based nano materials and other metal oxides. It also signifies the role of nano based antimicrobials viz. Nano-oxides of silver and titanium used for disinfection purposes and the adoption of nano photocatalysts for chemical degradation of contaminants. The review also highlights the safety concerns and risks associated with nanomaterials and their impacts on the environment. Furthermore, it also presents an overview of the major environmental implications of nanotechnology by analysis of published research works from all aspects and a detailed overview of the recent development in the field of nanotechnology-based wastewater treatment.

2 Role of nanomaterials

Different materials such as zeolites, activated carbon, pillared clays, mesoporous oxides, metal-organic frameworks and polymers have been developed and employed for water treatment (Madannejad, Shoaie et al. 2019). These materials have shown variable degrees of potential for removing different harmful contaminants.

2.1 Carbon-based materials used for removal of organic and inorganic pollutants

Carbon-based materials have been proved to be the best adsorbents for removing these organic and inorganic pollutants (Kadam, Saratale et al. 2019, Kalaitzidou, Zouboulis et al. 2020, Wang, Tang et al. 2020). Carbon-based nanomaterials such as activated carbon, graphene, fullerenes and carbon nanotubes (CNT) exhibit high specific surface area, high porosity, adjustable pore size, high electronic conductivity and good chemical stability in acid/alkaline conditions (Wang, Ng et al. 2012, Lam and Luong 2014). Metal organic frameworks (MOFs) derived-carbons comprise of carbon skeletons encapsulating metal or metal oxide nanoparticles, non-metal doped carbon hybrid materials, metal-free porous carbons and other composites (Hao, Qiu et al. 2020). These carbon-based frameworks are prepared by self-assembly of metal clusters and organic ligands. Metal clusters in these multi-dimensional structures are used as linkage point and organic ligands are used as supports. High specific surface area, abundant pore structure, adjustable morphology and versatility of carbon-based MOFs have attracted extensive research interest and their application in the fields of gas storage, sensing, energy storage, adsorption and catalysis (Fan, Wang et al. 2018, Li, Wang et al. 2018, Man, He et al. 2019, Solis, Kwon et al. 2020, Tang and Wang 2020).

The inherent diversity of MOFs provides the basis for precise control of the physical and chemical properties of materials. The changes in organic ligands, functional monomers and carbonization conditions create more possibilities for doping heteroatoms and improving performance, greatly expanding the types of materials (Fan, Du et al. 2018, Ren, Tao et al. 2018, Lai, Wang et al. 2019, Su, Ru et al. 2019, Pandi, Prabhu et al. 2020). Further, the recovery of heavy metals like uranium from wastewater using strong carbon-based adsorbents like graphitic carbons has been widely achieved. The development of carbon-based novel materials with highly efficient and excellent selectivity for capturing U(VI) from nuclear-related wastewater and seawater is highly desirable (Qiu, Liu et al. 2021). These materials have been widely used as effective adsorbents; however, the wide-scale application is still limited by the high costs of wastewater treatment and there is a growing emphasis to design low-cost adsorbents (Hu, Ai et al. 2020).

2.2 Graphene-based nanomaterials

The use of graphene as a carbon-based nanomaterial for pollutant removal depends on its production cost, removal efficiency and environmental impacts. The low manufacturing cost of graphene oxide (GO) based environmental technologies makes them comparable to pristine graphene. Graphene is a superior material and an alternate to CNT for waste-water treatment. The usage of graphene-based materials as adsorbents offers various advantages in contrast to CNTs. The first layer of graphene nanomaterials has two basal planes for the adsorption of contaminants. Comparatively, the adsorbents cannot reach the innermost walls in CNTs (Sitko, Zawisza et al. 2013).

Furthermore, the chemical exfoliation of graphite was used to synthesize graphene oxide (GO) and reduced graphene oxide (RGO), without any prerequisite for metallic catalysts or sophisticated machinery. Therefore, the graphene produces are free of catalyst residues and do not require further treatment. The application of graphene-based materials has raised research interest not only in the field of chemistry but also in environmental water quality management. Graphene has numerous π- bonds and functional groups containing sufficient oxygen besides having a large surface area (Lu, Jin et al. 2018). For the adsorption of graphene-based nanomaterials five different interactions could occur; π-π bonds, hydrophobic effects, electrostatic, hydrogen and covalent bonds as shown in Fig. 1 (Zhu, Murali et al. 2010).

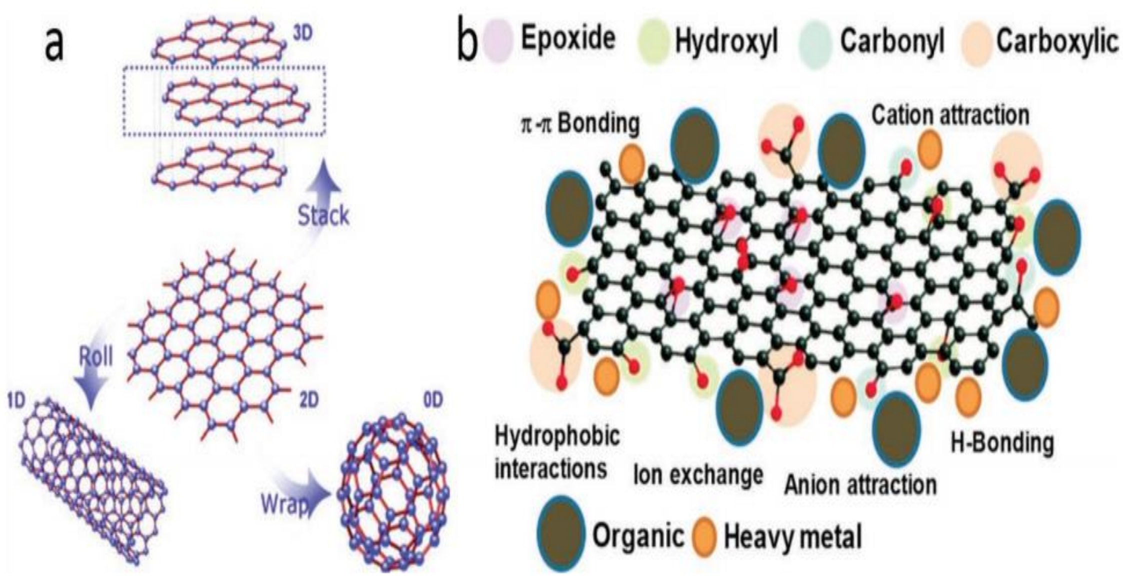

Fig. 1. Significant properties of graphene-based nanoparticles; (a) Dimension shapes i.e., 0D inwrap, 1D in Roll, 2D in sheet, 3D in Stack shapes and (b) attractions (Zhang, Chi et al. 2014, Yin, Cui et al. 2020).

Fig. 1 illustrates a strong sigma "σ" bond of graphene is formed in a 2-dimension plane due to share three of four valence shell electrons while weak pi "π" bond formed in the 3D when valence electron is delocalized among all atoms (Bhattacharyya and Gupta 2011). Adsorption depends upon the contribution of provided surface area and the number of functional groups to adhere pollutants. Although the chemical bonding of organic and CNT/graphene are done by the functional group such as hydroxyl-OH or carbonyl – COOH group (Wadhawan, Jain et al. 2020). Physiochemically, graphene and its oxides boost hydrophilic nature and the adsorption capacity of certain pollutants. The oxidation method helps in the stability of physical as well as chemical properties of graphene (Yang, Guo et al. 2020). Normally, for the removal of various pollutants from wastewater, graphene based nanomaterials are more preferred some of the relevant studies are shown in Table 2.

Table 2. Applications and modification of graphene as adsorbents for removal of an inorganic contaminant.

Target contaminant	Adsorbent	Adsorption capacity (mg/g)	Mechanism	Reference
Methylene blue	G-CNT	81.97	Self-induced π-π interaction	(Ai and Jiang 2012)
Methylene blue, and Rhodamine B	RGO-hydrogels	7.85, and 29.44, respectively	Anion–cation interactions, Strong π-π interaction	(Tiwari, Mahesh et al. 2013)
Pb(II)	RGO/PAM	1000	Ion exchange	(Yang, Xie et al. 2013)
Cu(II)	PVP-RGO	1689	Cation-π interaction, physisorption	(Zhang, Chi et al. 2014)
Cr(VI)	PEI-GO	539.53	π-electrons, electrostatic interaction	(Chen, Li et al. 2014)

Pb(II), As(III), and As(V)	GO-$MnFe_2O_4$	673, 146, and 207, respectively	Cation exchange reaction	(Kumar, Nair et al. 2014)
Fuchsine	GMN	89.4	Van der Waals interactions	(Wang, Zhang et al. 2011)

Table 2 shows the application results of graphene, their oxides and reduced graphene oxide. PVP-RGO has shown a relatively high absorption value compared to others. The target contaminant for adsorption of PVP-RGO was Copper. It has been observed that PVP-RGO increased the surface area which gives rise to the high value of adsorption of Cu target contaminant. The higher adsorption rate and higher surface area are developed due to "Cu" cation and functional group "π" pi bond interaction (Zhu, Murali et al. 2010, Zhang, Chi et al. 2014). The availability of the active site and surface area are directly proportional to each other. The decrease in the removal of target contaminant is due to the limitation of the active site, no matter how much pollutant concentration is high (Zhang, Chi et al. 2014, Yin, Cui et al. 2020). G-CNT has shown the lowest adsorption value for target contaminated methylene blue compared to the PVP-RGO. The pi "π-π" pi interaction occurred due to a decrease in spacing between G–CNT hybrid henceforth adsorption values were observed. At initial stage, the adsorption rate is high as a result of an increase in the driving force of concentration rise to overcome the mass transfer between two phases i.e. solid phase and the aqueous phase (Yin, Cui et al. 2020).

2.3 Carbon nanotubes

Nanotubes of carbon can be categorized into three types, namely, carbon nanotube composite, multi-walled carbon nanotube (MWCNT) and single-walled carbon nanotube (SWCNT) (Fenati, Sherrell et al. 2021, Mudasir and Naqash 2021). Because of their one-dimensional form, CNTs have excellent physical properties, such as electrical, thermal and mechanical properties (Thostenson, Ren et al. 2001, Huang, Singer et al. 2021). In deciding the features of the CNTs, dimensional characteristics play a major role. It has been stated that CNTs show an improvement in metal removal efficiency with an increase in surface modification. Reasonable surface modifications by appropriate functional groups can be made to allow the efficient accessibility of different contaminants into carbon nanotubes (Chen, Feng et al. 2012). Several experiments showed that heavy metal ions are adsorbed by carbon nanotubes with very potent nanomaterials, including Pb^{2+}, Cu^{2+}, Zn^{2+} and Cd^{2+} (Xu, Cao et al. 2018, Abukhadra, Bakry et al. 2019). The methods of surface modification in carbon nanotubes are chemical grafting, oxidization, and physical modification like coating (Yu, Huang et al. 2011). Four potential adsorption sites constitute the outermost wall, interstitial channels, inner cavities, and CNT grooves (Kumar, Nair et al. 2014).

The mechanism of adsorption in CNTs is similar to that of graphene. Adsorption, even in certain instances, relies on the functional dimensions of CNTs, where porous nature plays an important role (Den, Liu et al. 2006). Carbon nanotubes have traditionally been used as a combination of condensed solids, so it is often challenging to distinguish them from water effectively. New granular carbon nanotubes/Al_2O_3 composites are prepared for two pharmaceuticals (carbamazepine and diclofenac sodium) with suitable sorption efficiency, mechanical strength, heat resistance and hydrophilicity. During the regeneration process, the adsorbed pharmaceuticals can be decomposed (Wei, Deng et al. 2013). This process of hybridization influenced the creation of granular composites based on CNTs. The environmental functions of different CNTs are listed in Table 3. It can be inferred that several problems still exist and arise from the environmental application of CNTs and further research for novel CNT adsorbents such as new forms of composites of CNTs is required.

Table 3. Diversity of carbon nanotubes (CNTs) used for organic contaminant removal.

Type of CNTs	Target Contaminants	Removal rate/ adsorption capacity	Reference
SWCNTs	17α-ethinyl estradiol and Bisphenol A	EE2 (95–98%), BPA (75–80%)	(Joseph, Heo et al. 2011)
MWCNT	Polychlorinated biphenyls, Phenols and non-steroidal anti-inflammatory drugs	80–99%	(Ghaedi, Shokrollahi et al. 2011)
Granular CNTs	Diclofenac sodium (DS) and carbamazepine (CBZ)	DS:106.5 μmol/g CBA:157.4 μmol/g	(Wei, Deng et al. 2013)
MWCNTs	Eriochrome cyanine R (ECR)	73.18 mg/g	(Ghaedi, Shokrollahi et al. 2011)
MWCNTs	5-(4-dimethyl amino benzylidene) rhodamine	15.52 mg/g	(Ghaedi, Ghobadzadeh et al. 2013)
MWCNTs	Humic acid (HA)	80–85%	(Yang, Hu et al. 2011)
MWCNTs	Direct Red 23	85.5 mg/g	(Konicki, Pełech et al. 2012)

2.4 Metal and metal oxides nanoparticles

For heavy metal reduction from wastewater during treatment, zero-valent metals are considered the best adsorbent for remediation due to having high reactivity, degradation abilities, magnetic properties, and reduction of catalytic activity by oxidization and agglomeration of zerovalent metal. Among all zero-valent metals like Fe^0, Sn^0, Ti^0, Ni^0, Al^0, Zn^0, Mg^0 and Pd^0 (Rambabu, Bharath et al. 2021); remarkably the fourth most abundant element in this earth crust zero-valent iron is most commonly used due to having high reactivity and adsorption properties. Heterogenous catalyst i.e., Fe zero-valent metal (ZVI) eliminates organic and inorganic pollutants from the environment by wastewater treatment. ZVI activates the peroxymonosulfate (PMS) for reduction of levofloxacin (LEV) (Tan, Ruan et al. 2021), degrade dyes, removal of uranium (Zhang, Ruan et al. 2019), phenol(Pang, Ruan et al. 2019), and bisphenol (Ma, Cui et al. 2018) from wastewater. Due to low stability and mobility limitations, zero-valent metals are synthesized into zero-valent metal nanoparticles (ZVM NPS). It enhances the stability, adsorption power, high surface area, degradation ability, magnetic properties and electrostatic properties (Liu et al., 2018; Diao, et al., 2016). For example, ZVI Sn NPS (zero-valent tin nanoparticles) (Mahmoud and Abdelwahab 2021) is used to remove heavy metals such as lead from waste water. So far, different nanomaterials are used for waste water treatment by removal of various sorts of effluent or organic and inorganic pollutants.

2.4.1 Nano metal oxides

Nano-sized metal oxides (NMOs), including aluminium oxides, ferric oxides, manganese oxides, titanium oxides, and cerium oxides are the promising ones among the available adsorbents for pollutant removal (Agrawal and Sahu 2006). This is partially due to the size quantization effect caused by their high activity and large surface area (El-Sayed 2001). Current studies have proposed that various nano metal oxides e.g. iron oxide, manganese oxide shows a high affinity for heavy metal removal thus, making them possible to comply with ever more stringent regulations (Deliyanni, Peleka et al. 2009). However, it has been reported that an increase in surface energy effects stability. The size of metal oxides decreases from micrometre to nanometer because it shows poor stability due to surface energy (Pradeep 2009). NMOs are vulnerable to aggregation, and the high potential and acuteness of NMOs would be greatly reduced or even lost.

Due to poor mechanical strength and excessive pressure drops, the NMOs in fixed beds or any other flow through systems have been reported to be inefficient. The applicability of NMOs for wastewater treatment can be enhanced by combining them in large porous supports and thus obtain composites (Pan, Pan et al. 2009). The commonly used porous supports comprise of natural materials, activated carbon and polymeric synthetic hosts. In comparison to traditional NMOs, magnetic nano metal oxides can easily detach from water when exposed to a magnetic field (Mahdavian and Mirrahimi 2010). Magnetic composite adsorbents based on NMOs allow easy isolation from aqueous recycling or regeneration solutions. Such simple separation is important for improving the quality of operations and reducing the costs of wastewater treatment. As there are various forms of NMOs used for the removal of heavy metals, comparing their capacity is significant.

Nevertheless, the experimental conditions in the different sources varied considerably, therefore, a straightforward analysis of the reported findings seems to be a little futile. For example, due to the various synthetic methods of a given NMO, its size and surface chemistry are difficult to maintain constant. Additionally, the operating conditions, such as the temperature, chemistry of the solution (pH, ion types and their strength), experimental process (batch or column runs) are very different. A simple comparison has been made here about NMOs for metal removal as summarized in Table 4. It is observed that at the same temperature, different adsorbents show different adsorption capacities against the adsorbate. By Ferric oxide (Fe_2O_3) 2.6 mg/g while by ferric oxyhydroxide 149.25 mg/g adsorption capacity was observed at 25 °C.

2.4.2 Nanometal oxides act as supporting material

Nanometal oxides (NMOs) have been found quite successful for the removal of different contaminants. There are, however, certain limitations associated with the use of NMOs due to the presence of fine and ultra-fine particles. The limitations lead to issues such as the lack of operation due to agglomeration, excessive pressure drops and difficult separation when applied in flow-through systems (Cumbal and SenGupta 2005). A successful way to deal with these limitations is to create hybrid adsorbents by combining NMOs particles into/onto permeable membranes of bigger size (Hansen, Kwan et al. 2001). The broadly utilized supports incorporate normal hosts, for example, bentonite, sand and metallic oxide materials. Some host-upheld NMOs for the expulsion of heavy metals are listed in

Table **4**.

Table 4. Adsorption capacities to remove heavy metal ions using nanometal oxides as support materials.

Metal oxide	**Adsorbate**	**Support material**	**Adsorbents**	**Adsorption capacity (mg/g)**	**Temperature (°C)**	**Reference**
Iron oxide		Treated urban sludge from waste	Pb (II) and Cd (II)	42.4 and 14.7		(Agouborde and Navia 2009)
Fe_3O_4		Cyclodextrin	Cu (II)	47.2		(Badruddoza, Tay et al. 2011)
Fe_2O_3		Sepiolite	Pb (II) and Cd (II)	18.30		(Lazarevic, Janković-

					Častvan et al. 2010)
Manganese oxide	Diatomite	Ni (II)	99.0 and 27.86		(Khraisheh, Al-degs et al. 2004)
Goethite	Sand	Pb (II) and Cd (II)	702 and 704 401.14		(Lai, Chen et al. 2001)
	_		26.8	25	(Wadhawan,
Pb (II)	_	TiO_2	9.2	25	S., et al.2020)
Cu (II)	_	Fe_2O_3	6.7	28	(Yang, X., et al.2020)
Pd (II)	_	CeO_2	84.46	28	(Ai, L. and J. Jiang.,2012)
Pd (II)	_	ZnO	149.25	25	(Tiwari, J.N., et al 2013)
Cu (II) Cu (II)	_	Hematite (α-Fe_2O_3) Goethite (α-FeOOH)		25	(Yang, Y., et al.2013)

The efficient and specific adsorption to various aquatic contaminants is shown by nano metal oxides (NMOs). However, these are typically present as small or ultra-fine particles, often leading to problems such as lack of activity due to agglomeration, difficult isolation, and extreme pressure decreases when added to flow through structures. The manufacture of hybrid adsorbents on larger porous supports by impregnating or covering NMO particles is an efficient way to solve these technical bottlenecks (Jones, Ray et al. 2008). Natural hosts such as bentonite (Hu, Jimmy et al. 2003, Ebrahimpour, Pliekhova et al. 2021), metallic oxide compounds such as membranes of Al_2O_3 (Yu, Jimmy et al. 2005, Singh, Juneja et al. 2021), the complex porous manganese oxide

(Wang, Zhang et al. 2011) and hosts of synthetic polymers such as cross-connected resins for ion exchange (Liu, Ye et al. 2010, Wang, Shi et al. 2011) are commonly used supports. **Error! Reference source not found.**summarizes several host-supported NMOs for removing heavy metals.

Table 5. Organic contaminants removal using nano metal oxides as supporting material.

Adsorbents	Organic pollutants	Adsorption capacity (mg/g)	Reference
SiO_2/γ-Fe_2O_3/chitosan composite	MO	34.29	(Zhu, Jiang et al. 2011)
Magnetic nanopowder	Phenols	13.50	(Mihoc, Ianoş et al. 2014)
γ-Fe_2O_3/2C nanocomposite	Phenols	42.34	(Istratie, Stoia et al. 2019)
Fe_3O_4@SiO_2/SiCRG	Metoprolol (MTP)	447	(Soares, Simões et al. 2016)
SiO_2/SiCRG	MTP	393	(Soares, Simões et al. 2016)
Silica gel	MTP	68.40	(Kutzner, Schaffer et al. 2014)
α - Fe_2O_3	Congo red	413.22	(Satheesh, Vignesh et al. 2016)
Fe_3O_4 MNPs	Crystal violet	166.67	(Muthukumaran, Sivakumar et al. 2016)

Until now, metal oxides (MOs) are broadly investigated as exceptionally effective adsorbents for the expulsion of contaminants from water and wastewater. They display different favourable merits, for example, quick energy, high adsorption limit, and best sorption towards contaminations in wastewater. Metal oxides have been considered quite effective for the removal of pollutants from contaminated waters. They have several unique properties such as high adsorption capacity, affinity towards pollutants and fast kinetics. However, to promote the large scale applicability of metal oxides, there is a serious need to solve various limitations associated with the technicalities involved. For example, metal oxides aggregate to form large size particles and lose their pollutant removal efficiency when applied in aqueous solutions. The treatment process for contaminants from wastewater remains a subject of discussion and research. There is also an urgent need for the production of new metal oxide-based adsorbents to solve the technicalities associated with pollutant removal using metal oxides.

However, the associated research works with the development of composite adsorbents still seem to be in a development phase performed either on a lab or pilot scale. Recently, magnetic adsorbents for water treatment have attracted several researchers due to their simple separation mechanism. The pollutant removal problems associated with graphene can be overcome with the incorporation of magnetic particles into GO or GNs. The incorporation of magnetic nanoparticles can also reduce the possibility of restacking and agglomeration and thus provide a high surface area and increase pollutant adsorption capacity (Shen, Huang et al. 2015). Thermodynamics, adsorption kinetics, and equilibrium were investigated by Liu et al., (Liu, Bai et al. 2010) due to the addition of Fe_3O_4/GO composite (M/GO) magnetite to extract Co^{2+} from aqueous solutions. After adsorption, M/GO could be recovered by magnetic separation and was therefore found to have greater adsorption than Fe_3O_4.

$MnFe_2O_4$-G ferrites have been widely applied for the efficient removal of Cd and Pb ions from wastewaters. The monolayer adsorption capacity of Cd and Pb on $MnFe_2O_4$-G was reported as 76.90 and 100 mg/g at pH of 7 and 5, respectively. The pseudo-second-order kinetic model was followed for the adsorption of Cd and Pb ions on $MnFe_2O_4$-G surface. As shown in Fig. 2, $MnFe_2O_4$-G was also reported to be very effective for *E.coli* populations and a loss of 82% viability with 100 mg/L for 2 hours was observed (Xiong, Zhang et al. 2010). It is observed that Fe_2O_3 ferric oxide shows greater adsorption capacity for organic pollutants like for congo red 413.22 and phenols 42.34. Meanwhile, magnetic nanopowder showed a low adsorption capacity for phenols which was 13.50 mg/g.

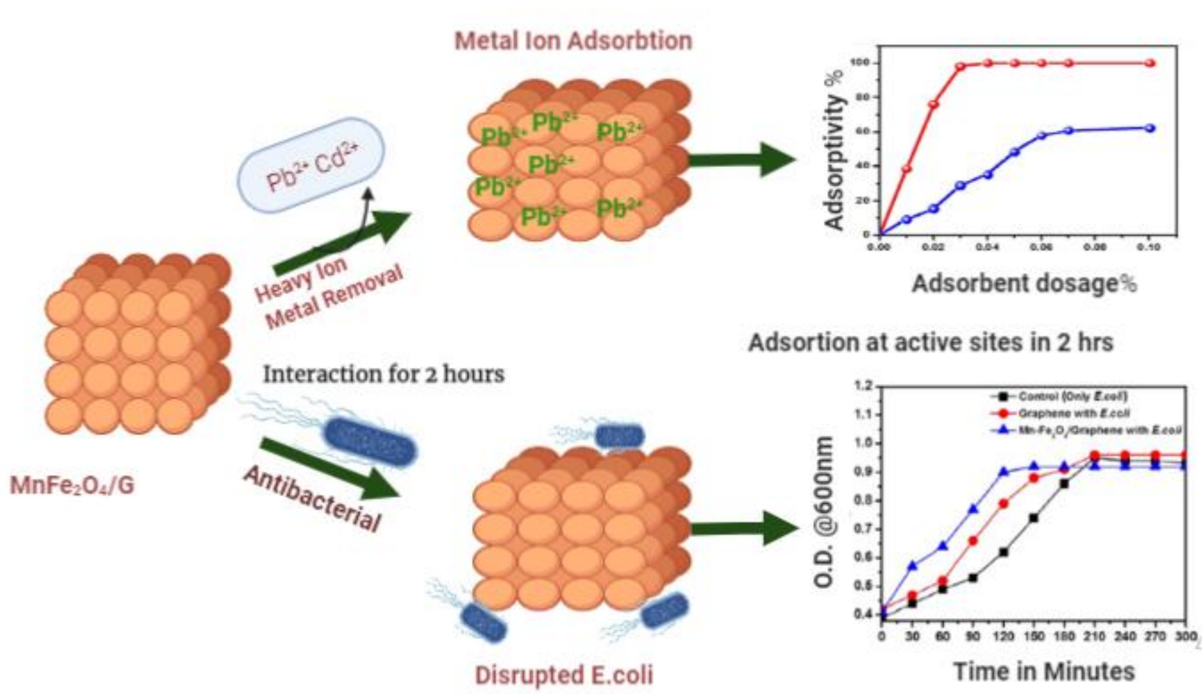

Fig. 2. The effect of $MnFe_2O_4$-G on adsorption activity (Chella, Kollu et al. 2015).

Furthermore, Fig. 2 demonstrates the effect of manganese ferrite/graphene ($MnFe_2O_4$-G) nanoparticles on adsorption. The antibacterial activity of manganese ferrite/graphene ($MnFe_2O_4$-G) nanoparticles is also shown with respect to time. Maximum adsorption capacity is shown in both aspects either for removal of heavy metal or antibacterial activity. The use of nanoparticles of metal oxides for water treatment and other applications is growing rapidly (Srivastav, Patel et al. 2020). However, certain harmful effects of metal oxide nanoparticles need to be assessed on living organisms. There are numerous studies on the toxicity and cytotoxic potential of metal oxide nanoparticles (Taju, Majeed et al. 2014). Eco-friendly metal oxide nanoparticles with reduced adverse effects and improved performance are therefore a challenge today.

3 Nanomaterials as photocatalysts

Photocatalytic degradation has been reported as an effective method for the treatment of various toxic organic compounds in recent decades (Table 6). The photodegradation of dyes with TiO_2 nanoparticles under visible or UV irradiation has been widely experimented as a result of the ineffectiveness of biological conventional treatment methods for degrading pollutants in wastewater (Zou, Zhang et al. 2011, Lee, Hong et al. 2012). The method of degradation of dyes with photocatalyst materials is described by several proposed mechanisms (Lázaro-Navas, Prashar et al. 2015). Adsorption on the photocatalyst surfaces of organic compounds and reaction by exciting superficial e/h+ pairs or OH radical forming ending products are also indicated by another mechanism (Rico-Oller, Boudjemaa et al. 2016). The type of reaction mechanism taking place depends on both solution-phase species and the surface adsorbed resulting in the differences in photodegradation kinetics.

Anatase, rutile and brookite are the three crystalline phases of TiO_2, with electronic band gap energies of 3.2, 3.0 and 3.2 eV respectively. By electronically connecting a narrow band gap semiconductor to TiO_2, semiconductor heterojunctions allow visible light exciton generation. The small bandgap allows low-energy photons to produce electron/hole pairs, which can then be introduced into TiO_2 based on the redox potential of the conduction (CB) and valence (VB) bands. (Marand and Almasi). With an onset wavelength of 385 nm, unmodified TiO_2 has a wide optical bandgap and thus does not absorb light in the visible range, resulting in a stark, white colour. Visible light-driven photocatalytic oxidation of VOCs in the gas phase usually takes one of two approaches; (1) using a particular semiconductor as a catalyst or sensitizer with a narrower bandgap and (2) doping TiO_2 to establish inter-band states that allow electron transfer to the conduction band in several.

Table 6. Preparation and use of photocatalysts based on TiO_2 and other nanomaterials in the degradation of organic compounds.

Pollutants	**Catalysts**	**Preparation method**	**Reference**
Rhodamine B	TiO_2/RGO	Hydrothermal	(Wang, Shi et al. 2011)
Methyl orange	Kaolinite/TiO_2	Calcined at 200 ^{0}C	(Wang, Shi et al. 2011)
Rhodamine B	TiO_2	Electrospinning	(Liu, Ye et al. 2010)
Methylene blue	TiO_2/GO TiO_2	Low-temperature hydrolysis	(Liu, Bai et al. 2010)
Methylene blue	Grapheme/TiO_2	One-pot solvothermal	(Zou, Zhang et al. 2011)
Methylene blue	Grapheme/TiO_2	Non-hydrolytic sol–gel approach	(Lee, Hong et al. 2012)
Rhodamine B	TiO_2/SnO_2	Sol–gel	(Abdel-Messih, Ahmed et al. 2013)
Methylene blue	TiO_2/Ti-F	Titanium isopropoxide and NaF with nitric acid at pH 2	(Lázaro-Navas, Prashar et al. 2015)
Methylene blue	TiO_2/Zn/Pd	Isopropoxide of titanium and nitrate of zinc with nitric	(Rico-Oller, Boudjemaa et al. 2016)

		acid at pH 2 and reaction with [Pd(cod)Cl_2]	
Methylene blue	CuO	co-precipitation	
Methylene blue	CuO	natural irradiation method	(Vasantharaj, Shivakumar et al. 2021)
Methylene blue	Zinc acetate dehydrate and cetrimide	co-precipitation	(Mydeen and Vasantha 2019)
Dye wastewater	Zn $(NO_3)_2$ and NaOH	Wet chemical method	(Aremu, Akintayo et al. 2021)
Methylene blue	Fe3O4/Polyacrylic acid Cadmium		
Congo red (CR) and Methylene blue (MB) dyes	ZnO-$ZnFe_2O_4$	Bio-hydrothermal method /Batch adsorption method	(Sahoo, Panigrahi et al. 2021)
Cationic dye/ Methylene blue	doping of Samarium, $ZnFe_2O_4$	co-precipitation method	(Keerthana, Yuvakkumar et al. 2021)

The adsorption of organic compounds is an important parameter for evaluating the degradation rates of photocatalytic oxidation (Zhang, Zhang et al. 2012). Semiconductor-based nanomaterials have been found to have effective photocatalytic activity for removing different organic pollutants from wastewaters. Among the most common semiconductors, ZnO arises as one of the most promising materials for photocatalysis. Some appealing properties of ZnO are its strong oxidation capability, insolubility in water, low production costs, and photocatalytic activity in the near-UV spectral region (Zhong. et al., 2021). Although ZnO is a good photocatalyst, there is room for improvement, such as making it easy to recover from an aqueous phase. The preparation of ZnO embedded into a magnetic substrate may become an interesting option to explore. The ternary oxide ZnFe2O4 is an appropriate choice as it presents magnetic properties, as well as photocatalytic and antibacterial action. This ternary oxide is also able to maintain its magnetic properties even at high temperatures (Maynez-Navarro et al., 2020)

However, due to its unstable nature or inefficient illuminations application of the commercial visible light photocatalyst adoption becomes limited. Many studies investigated novel materials with high stability and high-quality degradation of organic contaminants as highly effective material under visible light, and active photocatalysts (Chen, Xiao et al. 2012). ZnCdS nanoparticles coated with reduced graphene oxide (RGO) sheets were prepared and were measured their photocatalytic activities on the 2D platform to photo-degrade organic dyes. Fig. 5 shows the experimental method used to prepare RGO-ZnCdS.

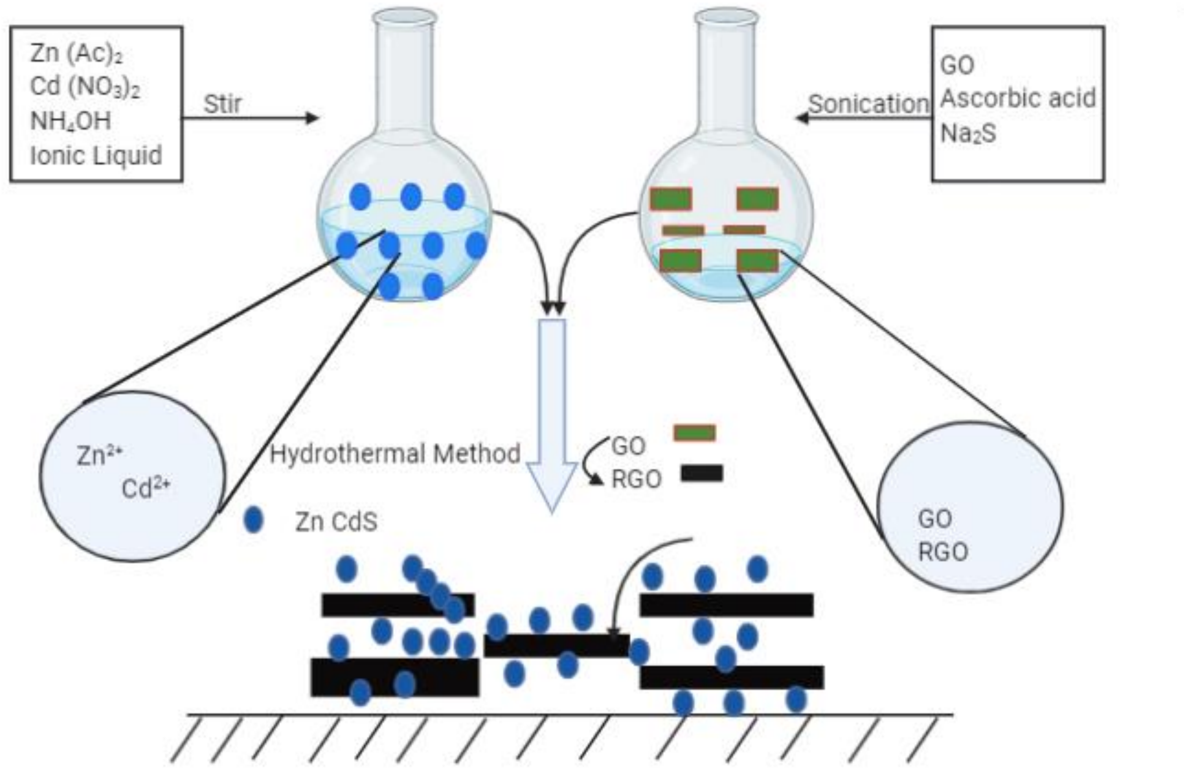

Fig. 3. The experimental procedure for the preparation of RGO–ZnCdS (Shen, Huang et al. 2015).

4 Antimicrobial nanomaterials

Disinfection methods currently available can effectively remove pathogens when applied to drinking water (Kidd, Westerhoff et al. 2020). The research works carried in recent decades have filled gaps in the water treatment methods between disinfection and disinfection by-products (DBPs) (Mazhar, Khan et al. 2020, Srivastav, Patel et al. 2020), (Tang, Long et al. 2020). Chlorine, ozone and chloramines are commonly used disinfectants in the water treatment industry. These disinfectants can, however, react with other substances and can lead to the generation of harmful DBPs, mostly carcinogenic (Verma and Balomajumder 2020). The antimicrobial techniques of such nanomaterials, their benefits, demerits, utility and significant research requirements for water treatment are carefully considered in these review articles (Kidd, Westerhoff et al. 2020, Verma and Balomajumder 2020).

4.1 Antimicrobial action of TiO_2 nanoparticles

Titanium dioxide is a highly prevalent form of nanoparticle in drinkable water, surface water, and other water supplies for inactivating microbes. The antibacterial function of titanium dioxide is due to reactive oxygen species (ROS) produced. The created ROS damage protein and DNA, destroy the plasmic membranes and release dangerous ions, interrupt electron flow and interfere with the function of the respiratory system. The activation of titanium dioxide occurred by solar radiation due to which high UV-absorbance was observed which significantly increased solar disinfection. Titanium dioxide-based solar disinfection is a very slow method that can have a low proportion of UV absorption in sunlight. The solar disinfection of titanium dioxide is important for the application of solar disinfection of titanium dioxide to enhance the visible light absorption of titanium dioxide or UV-A (Gao, Zheng et al. 2019, Wang, Lin et al. 2020). Bacterial death in the dark was also shown by the titanium dioxide nanomaterial, suggesting that such mysterious pathways could be feasible.

4.2 Antimicrobial action of silver nanoparticles

Ever since ancient times, silver has been known for its antimicrobial effect. The use of silver nanoparticles is diverse in manufacturing uses, both in medical care and in external medicine. As an antifungal nanomaterial, silver nanoparticles have been used in recent years. The substance used for water decontamination is as follows: high and wide-ranging antimicrobial activity, health and growth (Albukhari, Ismail et al. 2019, Kumar, Mishra et al. 2020, Metreveli, David et al. 2020, Najafpoor, Norouzian-Ostad et al. 2020). Nano-silver particles deactivate essential enzymes due to the absorption of ions. These ions are formed by bonding silver and hydrogen -SH groups when silver is ionized into water. The antimicrobial action of silver is illustrated in Fig. 3. Silver has the ability to break the cell membrane and prevent the mechanism of replication of DNA, as shown in Fig. 5. The toxicity of the silver nanoparticle depends on the rate at which silver ions are released. Silver ion release is influenced by the form, scale, padding and crystallographic facets. Pervasive ligands have higher toxicity and bioavailability when they are present. In ceramic micro-filters that can be used in developing countries silver nanoparticles have been used to shield bacteria.

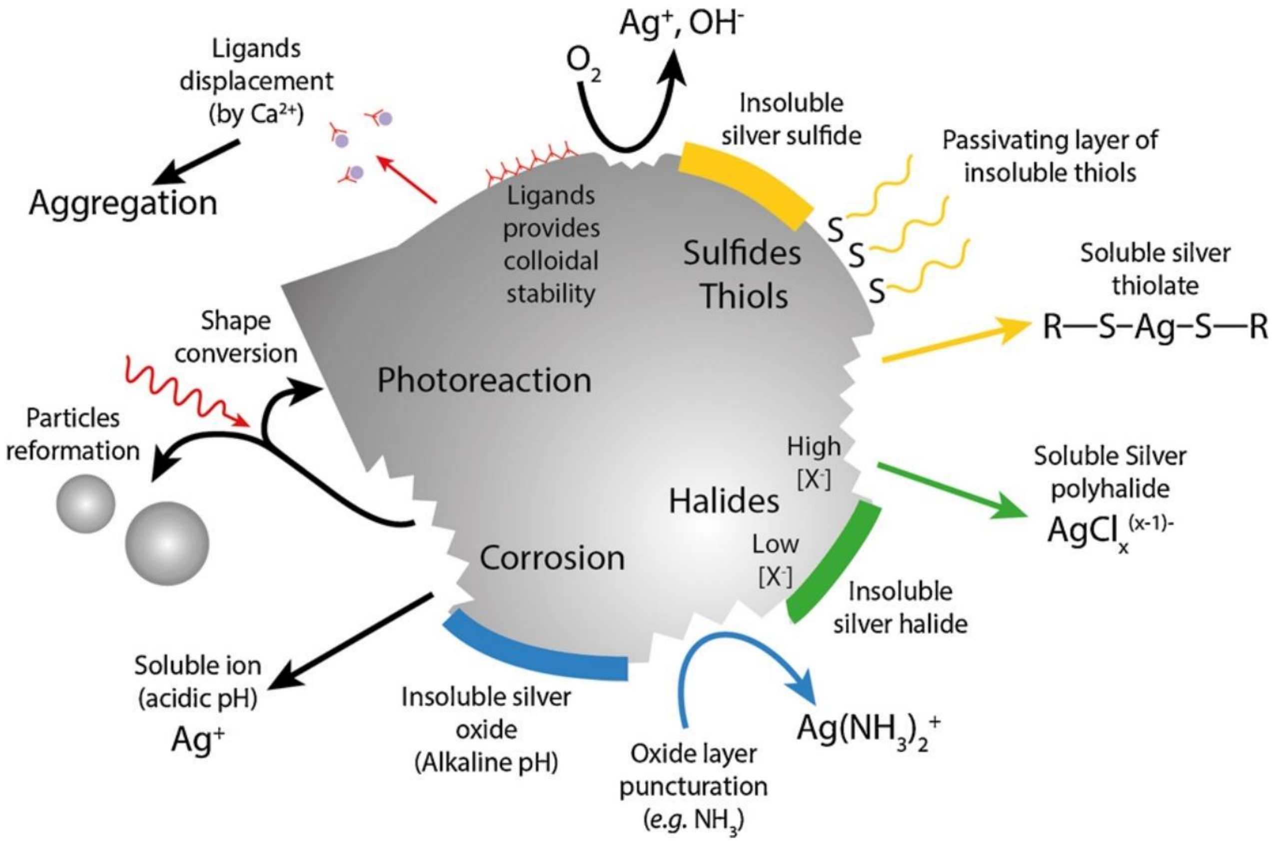

Fig. 4. Antimicrobial activity of silver nanoparticles (Le Ouay and Stellacci 2015).

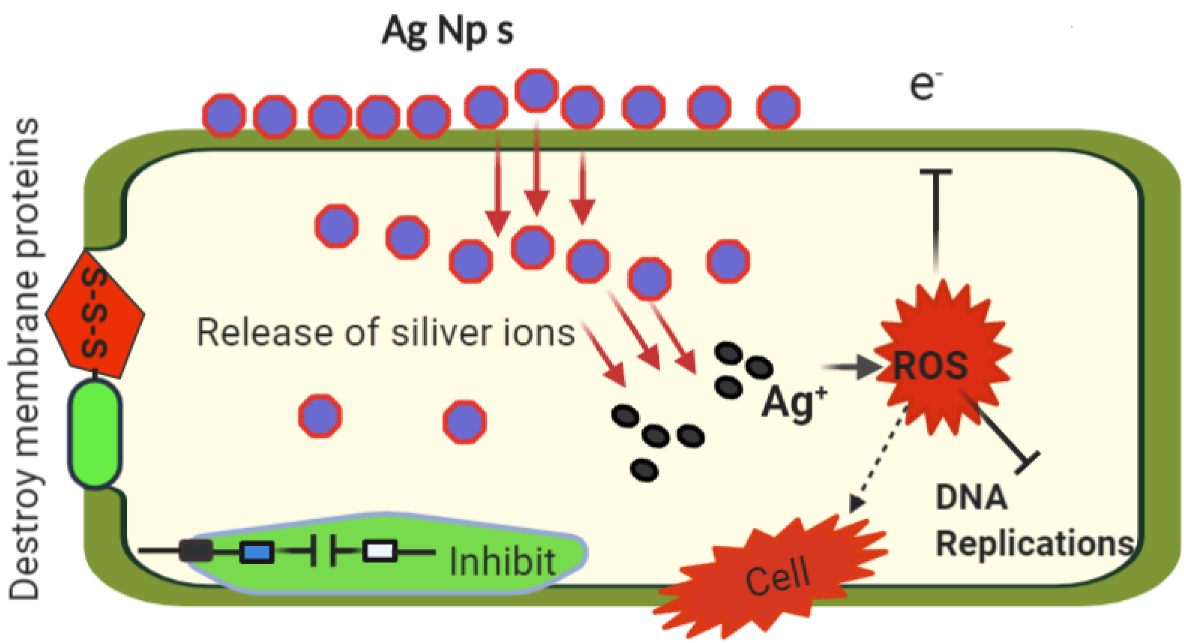

Fig. 5. Schematic diagram showing the mechanism of silver nanoparticles (Hamad et al., 2020).

4.3 Antimicrobial action of ZnO nanoparticles

Due to the high UV absorption potential and transparency of visible light, zinc oxide nanoparticles have been used in sunscreen lotions, paints and coatings. In a wide variety of bacteria, the nanoparticles of zinc oxide demonstrate excellent antibacterial efficacy. The photocatalytic production of H_2O_2 for the antimicrobial activity of zinc oxide has been proposed. Although there is an antibacterial activity of zinc oxide and Zn^{2+} nanoparticles, water species can be very susceptible to dissolved zinc (Rupa, Anandapadmanaban et al. 2019, Shkir, Al-Shehri et al. 2020). Due to vulnerable or insoluble characteristics, zinc oxide nanoparticles demonstrate a limitation in the treatment of drinking water.

5 Nanomaterials for heavy metal recovery

The development of nuclear energy has mitigated energy crisis and air pollution to a large extent. However, the excessive utilization of heavy metals like cadmium and uranium has resulted in the release of these constituents into subsurface environments, leading to environmental contamination (Dong, Dai et al. 2018, Bayramoglu and Arica 2019). Thus, the recovery of these heavy elements from wastewater is important to ensure the sustainable development of nuclear-related energy and reduce its negative consequences on the environment. For the recovery of heavy metals, the traditional methods employed viz. ion-exchange, solid-liquid extraction, biological enrichment and reductive precipitation, sorption as a convenient method were extensively used (Sholl and Lively 2016). However, these methods had limited practical applications for expensive costs, complex operation, and low treatment efficiency (Tabushi, Kobuke et al. 1979). This paved a way to the development of nanomaterial-based adsorbents with highly efficient and superior selectivity that are significantly desirable (Yuan, Yu et al. 2019, Yuan, Niu et al. 2020).

Nanomaterial like metal-free graphitic carbon nitride (g-C_3N_4) material has been demonstrated to be an effective heavy metal scavenger due to low cost, eco-friendly, high chemical and thermal stability (Hao, Chen et al. 2018, Hao, Zhang et al. 2019). Industrial wastewater containing heavy metals Like Hg, Cd and U are usually acidic, so it requires adsorbents of high stability. Advanced covalent organic frameworks (COFs) are connected by numerous strong covalent bonds that are highly stable in a range of aqueous phases. The regular channels and adjustable pore size make it easier for the adsorbed heavy metal ions to diffuse in COFs uniformly and be captured effectively. Huang et al., (Huang, Zhai et al. 2017) synthesized an extremely stable TAPB-BMTTPA-COF by integrating the methyl sulfide units onto the edge of the phenyl groups and then introducing S-containing functional groups onto the COF skeleton. The active sulfur sites could be fully exposed to capture Hg^{2+} with a saturated adsorption capacity of 734 mg/g (Dinari and Hatami 2019) synthesized a novel N-enriched COF material through the condensation of triazine and trialdehyde that could easily coordinate with Cd^{2+}.

In recent years, there have been a few reports about COFs being used as adsorbents for heavy metals. Jiang et al. (Cai, Jiang et al. 2019) synthesized Q-graphene (QG)-scaffolded COFs to detect Cu^{2+} in solution and blood. Liu et al. (Jiang, Liu et al. 2019) synthesized TpPa-NH_2@EDTA by using EDTA to modify COF. TpPa-NH_2@EDTA has a good adsorption effect on metal ions, such as soft Lewis acid (Ag+, Pd2+), borderline Lewis acid (Cu^{2+}, Ni^{2+}) and hard Lewis acid (Fe^{3+}, Cr^{3+}) with removal efficiencies of >85% within 5 min. Zhong et al. (Zhou, Zhong et al. 2018) synthesized a fluorescent thio-ether functionalized COF(TTB-COF) to pre-concentrate Au selectively in low concentrations with excellent stability. The strong coordination interaction between Au ions and S atoms in the thio-ether groups dominates the high Au adsorption (560 mg/g). (Yang, Chang et al. 2020) synthesized EB-COF: Br and applied it to remove As(V) from nearly neutral water. The $=N^+$ sites could produce electrostatic interaction with arsenate anions through the formation of hydrogen bonds with C-C=O groups.

6 Reuse and retention of nanomaterials

Reuse and retention of nanomaterials are two important parameters for the design of the nanotechnology-enabled device. This has come into a scenario because of the amount and related public health concerns. The application of separation devices or immobilization of nanomaterials in the treatment system has proven to help achieve this goal. Out of the separation processes, membrane filtration allows continuity in processing or continuous processing with small chemical use leaving behind a small footprint as well. Poly catalytic or catalytic ozonation shows more resistance to UV (Chin, Chiang et al. 2006, Hossain 2021) and chemical oxidants, ceramic membranes which have proven to be more advantageous than polymeric membranes. As the suspended particles can be retained by the membrane, these particles in a receiving system are detrimental to the membrane hybrid reactor system and hence reduce the reaction efficiency significantly.

Thus, to reduce the turbidity, initial water treatment is usually required. Other platforms like resins and membranes can also be used to immobilize nanomaterials to avoid further separation, but these techniques have led to a notable reduction in treatment efficiency. The need of the hour is the developmental research for simple and low-cost methods for nanomaterial immobilization and separation so that separation efficiency and performance are not compromised. One of the efficient methods is low field magnetic separation. However, it can be only applied to magnetic nanoparticles. To date, science has succeeded in learning just a bit about the release of nanomaterials from nanotechnology products although large expectations are there regarding the potential release depending on the method of immobilization and separation mechanism used. The nanomaterials embedded in a solid matrix are expected to have a minimal release until disposal.

Nanomaterials treated on a treatment system, surfaces are more likely to be released in a relatively fast and complete manner without applying downstream separation. Nanomaterials dissolution may release metal ions, and hence the careful control is needed (like by coating and size and shape optimization). The major technical hurdle that has remained challenging is the detection of nanomaterial release for risk assessment. Information about detection methods is outside the reach of this paper and the subject is alluded to in many recent reviews (Tiede, Boxall et al. 2008, Linley and Thomson 2021). In complex aqueous matrices, few advanced and expensive methods can detect nanomaterials, but these usually have several limitations. The development of quick, sensitive and selective nanomaterial analytical methods is the broad need of the present time.

7 Safety, toxicity and environmental impact of nanomaterials

Despite numerous benefits, the effect on humans and the ecosystem of nanoparticles remains one of the serious issues of nano-technology based water treatment due to their toxic nature (Table 7) (Gardner and Dhai 2014). This is due to a lack of knowledge and our less understanding of the behavioural consequences and future nanotechnology (Gardner and Dhai 2014). The key issues are danger and vulnerability to harm, along with the chemical and biological effects on humans and the environment. Hazards include leakage, spillage, circulation and nanoparticle aggregation. The properties such as shape, sizing (dimension), reactivity, etc. can make them harmful to living organisms, although these are the properties that actually make them useful (Hillie and Hlophe 2007, Eldessouky and Ali 2021). Nanoparticle introduction into the bloodstream or through skin, inhalation, ingestion, etc. can travel to various vital organs and eventually damage them (Ali 2012). The toxic nature of the nanoparticles leads to strong reactivity of chemicals and the development of ROS possible only from metal oxides and CNTs.

This results in damage to membranes, DNA and proteins due to oxidative stress and inflammation due to generated ROS (Nel, Xia et al. 2006, Eldessouky and Ali 2021). When absorbed on the body surface, nanoparticles can alter enzyme mechanisms and certain proteins (Hubbs, Mercer et al. 2011). By agglomeration, nanoparticles demonstrate their environmental toxicity. Risk evaluation is necessary because scientists lack awareness of the ecological threat of nanoparticles (Gardner and Dhai 2014). Before the use of nanoparticles begins on a wide scale in water purification, it is important to address major challenges, such as safety assessment, large-scale manufacturing facilities, safe waste disposal and energy proficiency (Gardner and Dhai 2014). The behaviour of nanoparticles in the human body needs to be known and addressed. More time is taken to address the concerned challenges, more will be the large-scale usage of nanoparticles delayed in water treatment.

Table 7. Self-toxic effect of nanomaterials.

Nanomaterial	Self-toxic effect observations	Reference
Carbon black Composite/TiO_2/Al_2O_3	More toxic at the level of microns	(Hubbs, Mercer et al. 2011)
Au/Carbon composite	Lower-range non-toxic	(Jia, Wang et al. 2005)
Carbon, Al_2O_3 composites, and metal	Concentration- and time-dependent.	(Ajdary, Moosavi et al. 2018)
Ag/Carbon composite	Dose and time-dependent but toxic	(Karlsson, Cronholm et al. 2008)
CdSe quantum dots	Acute toxicity observed	(Ray, Yu et al. 2009)
Hexadecylcetyltrimethyl ammonium bromide (CTAB)	Extremely poisonous in certain concentrations	(Takahashi, Niidome et al. 2006)
Fe_2O_3 and composite carbon nanotubes	Toxic effects and damage to DNA at the lowest concentrations	(Karlsson, Cronholm et al. 2008)
Single and multi-walled carbon nanotubes	Increase in toxicity at concentrations above 15 μg/cm	(Taju, Majeed et al. 2014)

8 Conclusion and future recommendations

Nanotechnology has emerged as a suitable and ideal method in the scenario of developing water treatment technologies. Nanomaterials present great opportunities in the field of water treatment due to their distinctive characteristics and convergence that could efficiently remove organic compounds, microorganisms and metal ions from water. Carbon-based nanoparticles viz. activated carbons, multiwall carbon nanotube, metal bases and COFs find tremendous applications to be used for the removal of wastewater pollutants including heavy metals. The development of modified nano-materials, their oxide and hybrid nano-based frameworks is the need of the hour to mitigate waste-water treatment issues. The challenges related to nanotechnology-based water treatment strategies include high cost, technical constraints and potential risk to humans and the environment. To address these challenges, and extensive research collaboration among government, research centres, industries and investors is desired. Overcoming the mentioned limitations would meet the criteria of green and sustainable chemistry. Further, nanotechnology-based water treatment technologies need to be developed continuously which could provide robust solutions to address the problems of water treatment. In future, nanomaterials are expected to offer great scope in environmental remediation and wastewater treatment.

Acknowledgement

The authors are grateful for the financial supports from the Foundation for Research Support of the State of Rio Grande do Sul – FAPERGS [19/2551-0001865-7] and National Council for Scientific and Technological Development – CNPq [303.622/2017-2] and the Engineering and Physical Sciences Research Council (EPSRC) UK.

References

Abdel-Messih, M., M. Ahmed and A. S. El-Sayed (2013). "Photocatalytic decolorization of Rhodamine B dye using novel mesoporous SnO2–TiO2 nano mixed oxides prepared by sol–gel method." Journal of Photochemistry and Photobiology A: Chemistry **260**: 1-8.

Abukhadra, M. R., B. M. Bakry, A. Adlii, S. M. Yakout and M. E. El-Zaidy (2019). "Facile conversion of kaolinite into clay nanotubes (KNTs) of enhanced adsorption properties for toxic heavy metals (Zn2+, Cd2+, Pb2+, and Cr6+) from water." Journal of hazardous materials **374**: 296-308.

Acharya, K., A. Blackburn, J. Mohammed, A. T. Haile, A. M. Hiruy and D. Werner (2020). "Metagenomic water quality monitoring with a portable laboratory." Water research **184**: 116112.

Agouborde, L. and R. Navia (2009). "Heavy metals retention capacity of a non-conventional sorbent developed from a mixture of industrial and agricultural wastes." Journal of hazardous materials **167**(1-3): 536-544.

Agrawal, A. and K. Sahu (2006). "Kinetic and isotherm studies of cadmium adsorption on manganese nodule residue." Journal of hazardous materials **137**(2): 915-924.

Ai, L. and J. Jiang (2012). "Removal of methylene blue from aqueous solution with self-assembled cylindrical graphene–carbon nanotube hybrid." Chemical Engineering Journal **192**: 156-163.

Ajdary, M., M. A. Moosavi, M. Rahmati, M. Falahati, M. Mahboubi, A. Mandegary, S. Jangjoo, R. Mohammadinejad and R. S. Varma (2018). "Health concerns of various nanoparticles: a review of their in vitro and in vivo toxicity." Nanomaterials **8**(9): 634.

Albukhari, S. M., M. Ismail, K. Akhtar and E. Y. Danish (2019). "Catalytic reduction of nitrophenols and dyes using silver nanoparticles@ cellulose polymer paper for the resolution of waste water treatment challenges." Colloids and Surfaces A: Physicochemical and Engineering Aspects **577**: 548-561.

Ali, I. (2012). "New generation adsorbents for water treatment." Chemical reviews **112**(10): 5073-5091.

Aremu, O. H., C. O. Akintayo, E. B. Naidoo, S. M. Nelana and O. S. Ayanda (2021). "Synthesis and applications of nano-sized zinc oxide in wastewater treatment: a review." International Journal of Environmental Science and Technology **18**(10): 3237-3256.

Badruddoza, A., A. Tay, P. Tan, K. Hidajat and M. Uddin (2011). "Carboxymethyl-β-cyclodextrin conjugated magnetic nanoparticles as nano-adsorbents for removal of copper ions: synthesis and adsorption studies." Journal of hazardous materials **185**(2-3): 1177-1186.

Basheer, A. A. (2018). "New generation nano-adsorbents for the removal of emerging contaminants in water." Journal of Molecular Liquids **261**: 583-593.

Bayramoglu, G. and M. Y. Arica (2019). "Star type polymer grafted and polyamidoxime modified silica coated-magnetic particles for adsorption of U (VI) ions from solution." Chemical Engineering Research and Design **147**: 146-159.

Bhat, S. A., B. Pandit, J. Khan, R. Kumar and R. Jan (2017). "Water requirements and irrigation scheduling of maize crop using CROPWAT model." Int. J. Curr. Microbiol. Appl. Sci **6**: 1662-1670.

Bhattacharyya, K. G. and S. S. Gupta (2011). "Removal of Cu (II) by natural and acid-activated clays: An insight of adsorption isotherm, kinetic and thermodynamics." Desalination **272**(1-3): 66-75.

Cai, Y., Y. Jiang, L. Feng, Y. Hua, H. Liu, C. Fan, M. Yin, S. Li, X. Lv and H. Wang (2019). "Q-graphene-scaffolded covalent organic frameworks as fluorescent probes and sorbents for the fluorimetry and removal of copper ions." Analytica chimica acta **1057**: 88-97.

Chella, S., P. Kollu, E. V. P. Komarala, S. Doshi, M. Saranya, S. Felix, R. Ramachandran, P. Saravanan, V. L. Koneru and V. Venugopal (2015). "Solvothermal synthesis of MnFe2O4-graphene composite—Investigation of its adsorption and antimicrobial properties." Applied Surface Science **327**: 27-36.

Chen, C., D. Li and X. Shao (2014). "High-performance nanocomposite films: reinforced with chitosan nanofiber extracted from prawn shells." Journal of Materials Science **49**(3): 1215-1221.

Chen, D., H. Feng and J. Li (2012). "Graphene oxide: preparation, functionalization, and electrochemical applications." Chemical reviews **112**(11): 6027-6053.

Chen, P., T.-Y. Xiao, H.-H. Li, J.-J. Yang, Z. Wang, H.-B. Yao and S.-H. Yu (2012). "Nitrogen-doped graphene/ZnSe nanocomposites: hydrothermal synthesis and their enhanced electrochemical and photocatalytic activities." ACS nano **6**(1): 712-719.

Cheriyamundath, S., S. L. J. W. Vavilala and E. Journal (2021). "Nanotechnology-based wastewater treatment." **35**(1): 123-132.

Chhabra, H. and M. Kumar (2020). "Size and shape dependent equation of state for nanomaterials with application to bulk materials." Journal of Physics and Chemistry of Solids **139**: 109308.

Chin, S. S., K. Chiang and A. G. Fane (2006). "The stability of polymeric membranes in a TiO2 photocatalysis process." Journal of Membrane Science **275**(1-2): 202-211.

Cumbal, L. and A. K. SenGupta (2005). "Arsenic removal using polymer-supported hydrated iron (III) oxide nanoparticles: role of Donnan membrane effect." Environmental science & technology **39**(17): 6508-6515.

Das, R., M. E. Ali, S. B. Abd Hamid, S. Ramakrishna and Z. Z. Chowdhury (2014). "Carbon nanotube membranes for water purification: A bright future in water desalination." Desalination **336**: 97-109.

Deliyanni, E., E. Peleka and K. Matis (2009). "Modeling the sorption of metal ions from aqueous solution by iron-based adsorbents." Journal of Hazardous materials **172**(2-3): 550-558.

Den, W., H.-C. Liu, S.-F. Chan, K. T. Kin and C. Huang (2006). "Adsorption of phthalate esters with multiwalled carbon nanotubes and its applications." Journal of Environmental Engineering and Management **16**(4): 275-282.

Deshpande, B., P. Agrawal, M. Yenkie and S. Dhoble (2020). "Prospective of nanotechnology in degradation of waste water: A new challenges." Nano-Structures & Nano-Objects **22**: 100442.

Dinari, M. and M. Hatami (2019). "Novel N-riched crystalline covalent organic framework as a highly porous adsorbent for effective cadmium removal." Journal of Environmental Chemical Engineering **7**(1): 102907.

Dong, A., T. Dai, M. Ren, X. Zhao, S. Zhao, Y. Yuan, Q. Chen and N. Wang (2018). "Functionalization and fabrication of soluble polymers of intrinsic microporosity for CO2 transformation and uranium extraction." Engineered Science **5**(2): 56-65.

Ebrahimpour, Z., O. Pliekhova, H. Cabrera, M. Abdelhamid, D. Korte, K. S. Gadedjisso-Tossou, J. Niemela, U. L. Stangar and M. Franko (2021). "Photodegradation mechanisms of reactive blue 19 dye under UV and simulated solar light irradiation." Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy **252**: 119481.

Edokpayi, J. N., R. Makungo, F. Mathivha, N. Rivers, T. Volenzo and J. O. Odiyo (2020). Influence of global climate change on water resources in South Africa: toward an adaptive management approach. Water Conservation and Wastewater Treatment in BRICS Nations, Elsevier**:** 83-115.

El-Sayed, M. A. (2001). "Some interesting properties of metals confined in time and nanometer space of different shapes." Accounts of chemical research **34**(4): 257-264.

Elbeltagi, A., N. Azad, A. Arshad, S. Mohammed, A. Mokhtar, C. Pande, H. R. Etedali, S. A. Bhat, A. R. M. T. Islam and J. Deng (2021). "Applications of Gaussian process regression for predicting blue water footprint: Case study in Ad Daqahliyah, Egypt." Agricultural Water Management **255**: 107052.

Eldessouky, R. and K. Ali (2021). "Potential Toxicity Evaluation for a Nano-modified Veneering Ceramic System. Experimental Study in Dogs." Egyptian Dental Journal **67**(1-January (Fixed Prosthodontics, Removable Prosthodontics and Dental Materials)): 531-536.

Fan, L., X. Du, Z. Kang, H. Guo, W. Kang, M. Xue and D. Sun (2018). "N-doped hollow carbon nanospheres as platinum anchoring material for efficient hydrogen evolution." Applied Surface Science **459**: 453-458.

Fan, W., X. Wang, X. Liu, B. Xu, X. Zhang, W. Wang, X. Wang, Y. Wang, F. Dai and D. Yuan (2018). "Regulating C_2H_2 and CO_2 storage and separation through pore environment modification in a microporous Ni-MOF." ACS Sustainable Chemistry & Engineering **7**(2): 2134-2140.

Fenati, R. A., P. C. Sherrell, D. A. Khodakov, J. G. Shapter and A. V. Ellis (2021). "Spatially isolated redox processes enabled by ambipolar charge transport in multi-walled carbon nanotube mats." Materials Horizons.

Gao, D., S. Zheng, L. Wang, C. Wang, H. Zhang and Q. Wang (2019). "SILAR preparation of visible-light-driven TiO_2 NTs/Ag_2WO_4-AgI photoelectrodes for waste water treatment and photoelectric conversion." Separation and Purification Technology **224**: 308-314.

Gardner, J. and A. Dhai (2014). "Nanotechnology and water: ethical and regulatory considerations." Application of Nanotechnology in Water Research: 1.

Ghaedi, M., P. Ghobadzadeh, S. N. Kokhdan and M. Soylak (2013). "Oxidized multiwalled carbon nanotubes as adsorbents for kinetic and equilibrium study of removal of 5-(4-dimethyl amino benzylidene) rhodanine." Arabian Journal for Science and Engineering **38**(7): 1691-1699.

Ghaedi, M., A. Shokrollahi, H. Hossainian and S. N. Kokhdan (2011). "Comparison of activated carbon and multiwalled carbon nanotubes for efficient removal of eriochrome cyanine R (ECR): Kinetic, isotherm, and thermodynamic study of the removal process." Journal of Chemical & Engineering Data **56**(7): 3227-3235.

Hansen, B. Ø., P. Kwan, M. M. Benjamin, C.-W. Li and G. V. Korshin (2001). "Use of iron oxide-coated sand to remove strontium from simulated Hanford tank wastes." Environmental science & technology **35**(24): 4905-4909.

Hao, M., M. Qiu, H. Yang, B. Hu and X. Wang (2020). "Recent advances on preparation and environmental applications of MOF-derived carbons in catalysis." Science of the total environment: 143333.

Hao, X., R. Chen, Q. Liu, J. Liu, H. Zhang, J. Yu, Z. Li and J. Wang (2018). "A novel U (vi)-imprinted graphitic carbon nitride composite for the selective and efficient removal of U (vi) from simulated seawater." Inorganic Chemistry Frontiers **5**(9): 2218-2226.

Hao, X., H. Zhang, Q. Liu, J. Liu, R. Chen, J. Yu, M. Zhang, P. Liu and J. Wang (2019). "In situ anchoring of pyrrhotite on graphitic carbon nitride nanosheet for efficient immobilization of uranium." Chemistry–A European Journal **25**(2): 590-597.

Hillie, T. and M. Hlophe (2007). "Nanotechnology and the challenge of clean water." Nature nanotechnology **2**(11): 663-664.

Hossain, M. F. (2021). Wastewater. Global Sustainability in Energy, Building, Infrastructure, Transportation, and Water Technology, Springer**:** 237-324.

Hu, B., Y. Ai, J. Jin, T. Hayat, A. Alsaedi, L. Zhuang and X. Wang (2020). "Efficient elimination of organic and inorganic pollutants by biochar and biochar-based materials." Biochar **2**(1): 47-64.

Hu, B., H. Wang, R. Liu and M. Qiu (2021). "Highly efficient U (VI) capture by amidoxime/carbon nitride composites: Evidence of EXAFS and modeling." Chemosphere **274**: 129743.

Hu, C., C. Y. Jimmy, Z. Hao and P. K. Wong (2003). "Photocatalytic degradation of triazine-containing azo dyes in aqueous TiO2 suspensions." Applied Catalysis B: Environmental **42**(1): 47-55.

Huang, F., G. Singer, Y. Zhou, Z. Sha, J. Chen, Z. Han, S. A. Brown, J. Zhang and C. H. Wang (2021). "Creating Ionic Pathways in Solid-State Polymer Electrolyte by using PVA-coated Carbon Nanofibers." Composites Science and Technology: 108710.

Huang, N., L. Zhai, H. Xu and D. Jiang (2017). "Stable covalent organic frameworks for exceptional mercury removal from aqueous solutions." Journal of the American Chemical Society **139**(6): 2428-2434.

Hubbs, A. F., R. R. Mercer, S. A. Benkovic, J. Harkema, K. Sriram, D. Schwegler-Berry, M. P. Goravanahally, T. R. Nurkiewicz, V. Castranova and L. M. Sargent (2011). "Nanotoxicology—a pathologist's perspective." Toxicologic pathology **39**(2): 301-324.

Istratie, R., M. Stoia, C. Păcurariu and C. Locovei (2019). "Single and simultaneous adsorption of methyl orange and phenol onto magnetic iron oxide/carbon nanocomposites." Arabian Journal of Chemistry **12**(8): 3704-3722.

Jia, G., H. Wang, L. Yan, X. Wang, R. Pei, T. Yan, Y. Zhao and X. Guo (2005). "Cytotoxicity of carbon nanomaterials: single-wall nanotube, multi-wall nanotube, and fullerene." Environmental science & technology **39**(5): 1378-1383.

Jiang, Y., D. Carrijo, S. Huang, J. Chen, N. Balaine, W. Zhang, K. J. van Groenigen and B. Linquist (2019). "Water management to mitigate the global warming potential of rice systems: A global meta-analysis." Field Crops Research **234**: 47-54.

Jiang, Y., C. Liu and A. Huang (2019). "EDTA-functionalized covalent organic framework for the removal of heavy-metal ions." ACS applied materials & interfaces **11**(35): 32186-32191.

Jones, N., B. Ray, K. T. Ranjit and A. C. Manna (2008). "Antibacterial activity of ZnO nanoparticle suspensions on a broad spectrum of microorganisms." FEMS microbiology letters **279**(1): 71-76.

Joseph, L., J. Heo, Y.-G. Park, J. R. Flora and Y. Yoon (2011). "Adsorption of bisphenol A and 17α-ethinyl estradiol on single walled carbon nanotubes from seawater and brackish water." Desalination **281**: 68-74.

Kadam, A., R. G. Saratale, S. Shinde, J. Yang, K. Hwang, B. Mistry, G. D. Saratale, S. Lone, D.-Y. Kim and J.-S. Sung (2019). "Adsorptive remediation of cobalt oxide nanoparticles by magnetized α-cellulose fibers from waste paper biomass." Bioresource technology **273**: 386-393.

Kalaitzidou, K., A. Zouboulis and M. Mitrakas (2020). "Cost evaluation for Se (IV) removal, by applying common drinking water treatment processes: Coagulation/precipitation or adsorption." Journal of Environmental Chemical Engineering **8**(5): 104209.

Kanchi, S. (2014). "Nanotechnology for water treatment." J. Environ. Anal. Chem **1**(2): 1-3.

Karlsson, H. L., P. Cronholm, J. Gustafsson and L. Moller (2008). "Copper oxide nanoparticles are highly toxic: a comparison between metal oxide nanoparticles and carbon nanotubes." Chemical research in toxicology **21**(9): 1726-1732.

Karthigadevi, G., S. Manikandan, N. Karmegam, R. Subbaiya, S. Chozhavendhan, B. Ravindran, S. W. Chang and M. K. Awasthi (2021). "Chemico-nanotreatment methods for the removal of persistent organic pollutants and xenobiotics in water – A review." Bioresource Technology **324**: 124678.

Keerthana, S. P., R. Yuvakkumar, P. S. Kumar, G. Ravi and D. Velauthapillai (2021). "Rare earth metal (Sm) doped zinc ferrite (ZnFe2O4) for improved photocatalytic elimination of toxic dye from aquatic system." Environmental Research **197**: 111047.

Khraisheh, M. A., Y. S. Al-degs and W. A. Mcminn (2004). "Remediation of wastewater containing heavy metals using raw and modified diatomite." Chemical Engineering Journal **99**(2): 177-184.

Kidd, J., P. Westerhoff and A. Maynard (2020). "Public perceptions for the use of Nanomaterials for in-home drinking water purification devices." NanoImpact: 100220.

Konicki, W., I. Pełech, E. Mijowska and I. Jasińska (2012). "Adsorption of anionic dye Direct Red 23 onto magnetic multi-walled carbon nanotubes-Fe3C nanocomposite: Kinetics, equilibrium and thermodynamics." Chemical Engineering Journal **210**: 87-95.

Kumar, A., B. Mishra and B. P. Tripathi (2020). "Polydopamine assisted synthesis of ultrafine silver nanoparticles for heterogeneous catalysis and water remediation." Nano-Structures & Nano-Objects **23**: 100489.

Kumar, S., R. R. Nair, P. B. Pillai, S. N. Gupta, M. Iyengar and A. Sood (2014). "Graphene oxide–MnFe2O4 magnetic nanohybrids for efficient removal of lead and arsenic from water." ACS applied materials & interfaces **6**(20): 17426-17436.

Kutzner, S., M. Schaffer, H. Börnick, T. Licha and E. Worch (2014). "Sorption of the organic cation metoprolol on silica gel from its aqueous solution considering the competition of inorganic cations." Water research **54**: 273-283.

Lai, C.-H., C.-Y. Chen, B.-L. Wei and C.-W. Lee (2001). "Adsorptive characteristics of cadmium and lead on the goethite-coated sand surface." Journal of Environmental Science and Health, Part A **36**(5): 747-763.

Lai, Y., F. Wang, Y. Zhang, P. Ou, P. Wu, Q. Fang, Z. Chen and S. Li (2019). "UiO-66 derived N-doped carbon nanoparticles coated by PANI for simultaneous adsorption and reduction of hexavalent chromium from waste water." Chemical Engineering Journal **378**: 122069.

Lam, E. and J. H. Luong (2014). "Carbon materials as catalyst supports and catalysts in the transformation of biomass to fuels and chemicals." ACS catalysis **4**(10): 3393-3410.

Lazarevic, S., I. Janković-Častvan, V. Djokic, Z. Radovanovic, D. Janackovic and R. Petrovic (2010). "Iron-modified sepiolite for Ni2+ sorption from aqueous solution: an equilibrium, kinetic, and thermodynamic study." Journal of Chemical & Engineering Data **55**(12): 5681-5689.

Lázaro-Navas, S., S. Prashar, M. Fajardo and S. Gómez-Ruiz (2015). "Visible light-driven photocatalytic degradation of the organic pollutant methylene blue with hybrid palladium–fluorine-doped titanium oxide nanoparticles." Journal of Nanoparticle Research **17**(2): 94.

Le Ouay, B. and F. Stellacci (2015). "Antibacterial activity of silver nanoparticles: A surface science insight." Nano Today **10**(3): 339-354.

Lee, E., J.-Y. Hong, H. Kang and J. Jang (2012). "Synthesis of TiO2 nanorod-decorated graphene sheets and their highly efficient photocatalytic activities under visible-light irradiation." Journal of hazardous materials **219**: 13-18.

Li, J., X. Wang, G. Zhao, C. Chen, Z. Chai, A. Alsaedi, T. Hayat and X. Wang (2018). "Metal–organic framework-based materials: superior adsorbents for the capture of toxic and radioactive metal ions." Chemical Society Reviews **47**(7): 2322-2356.

Linley, S. and N. R. Thomson (2021). "Environmental Applications of Nanotechnology: Nano-enabled Remediation Processes in Water, Soil and Air Treatment." Water, Air, & Soil Pollution **232**(2): 59.

Liu, F., S. Zhu, D. Li, G. Chen and S.-H. Ho (2020). "Detecting ferric iron by microalgal residue-derived fluorescent nanosensor with an advanced kinetic model." Iscience: 101174.

Liu, J., H. Bai, Y. Wang, Z. Liu, X. Zhang and D. D. Sun (2010). "Self-assembling TiO2 nanorods on large graphene oxide sheets at a two-phase interface and their anti-recombination in photocatalytic applications." Advanced Functional Materials **20**(23): 4175-4181.

Liu, R., H. Ye, X. Xiong and H. Liu (2010). "Fabrication of TiO2/ZnO composite nanofibers by electrospinning and their photocatalytic property." Materials Chemistry and Physics **121**(3): 432-439.

Liu, X., H. Pang, X. Liu, Q. Li, N. Zhang, L. Mao, M. Qiu, B. Hu, H. Yang and X. Wang (2021). "Orderly porous covalent organic frameworks-based materials: superior adsorbents for pollutants removal from aqueous solutions." The Innovation: 100076.

Lu, H., J. Wang, M. Stoller, T. Wang, Y. Bao and H. Hao (2016). "An overview of nanomaterials for water and wastewater treatment." Advances in Materials Science and Engineering **2016**.

Lu, S. Y., M. Jin, Y. Zhang, Y. B. Niu, J. C. Gao and C. M. Li (2018). "Chemically exfoliating biomass into a graphene-like porous active carbon with rational pore structure, good conductivity, and large surface area for high-performance supercapacitors." Advanced energy materials **8**(11): 1702545.

Ma, Q., L. Cui, S. Zhou, Y. Li, W. Shi, S. J. E. S. Ai and P. Research (2018). "Iron nanoparticles in situ encapsulated in lignin-derived hydrochar as an effective catalyst for phenol removal." **25**(21): 20833-20840.

Madannejad, R., N. Shoaie, F. Jahanpeyma, M. H. Darvishi, M. Azimzadeh and H. Javadi (2019). "Toxicity of carbon-based nanomaterials: Reviewing recent reports in medical and biological systems." Chemico-biological interactions **307**: 206-222.

Mahdavian, A. R. and M. A.-S. Mirrahimi (2010). "Efficient separation of heavy metal cations by anchoring polyacrylic acid on superparamagnetic magnetite nanoparticles through surface modification." Chemical engineering journal **159**(1-3): 264-271.

Mahmoud, M. E. and M. S. J. M. R. B. Abdelwahab (2021). "One-step synthesis of zero-valent Sn nanoparticles and potential microwave remediation of lead from water." **134**: 111090.

Man, P., B. He, Q. Zhang, Z. Zhou, C. Li, Q. Li, L. Wei and Y. Yao (2019). "A one-dimensional channel self-standing MOF cathode for ultrahigh-energy-density flexible Ni–Zn batteries." Journal of Materials Chemistry A **7**(48): 27217-27224.

Marand, S. A. and H. Almasi "A review on the application of metal nanoparticles in biodegradable films: The effects on antimicrobial, physicochemical and mechanical properties."

Mazhar, M. A., N. A. Khan, S. Ahmed, A. H. Khan, A. Hussain, F. Changani, M. Yousefi, S. Ahmadi and V. Vambol (2020). "Chlorination disinfection by-products in Municipal drinking water–A review." Journal of Cleaner Production: 123159.

Metreveli, G., J. David, R. Schneider, S. Kurtz and G. E. Schaumann (2020). "Morphology, structure, and composition of sulfidized silver nanoparticles and their aggregation dynamics in river water." Science of The Total Environment: 139989.

Mihoc, G., R. Ianoş and C. Păcurariu (2014). "Adsorption of phenol and p-chlorophenol from aqueous solutions by magnetic nanopowder." Water science and technology **69**(2): 385-391.

Mohanarangan, J. and G. Balakrishnan "Synthesis and Characterization of Copper oxide nanoparticles as Photocatalyst."

Morrison, E. S., M. R. Shields, T. S. Bianchi, Y. Liu, S. Newman, N. Tolic and R. K. Chu (2020). "Multiple biomarkers highlight the importance of water column processes in treatment wetland organic matter cycling." Water research **168**: 115153.

Mudasir, P. and J. Naqash (2021). "The effect of water cement ratio on the characteristics of multi-walled carbon nanotube reinforced concrete." Materials Today: Proceedings.

Muthukumaran, C., V. M. Sivakumar and M. Thirumarimurugan (2016). "Adsorption isotherms and kinetic studies of crystal violet dye removal from aqueous solution using surfactant modified magnetic nanoadsorbent." Journal of the Taiwan Institute of Chemical Engineers **63**: 354-362.

Mydeen, S. S. and M. J. I. J. I. T. E. E. Vasantha (2019). "Photocatalytic performances and antibacterial activities of nano-ZnO derived by cetrimide-based co-precipitation method by varying solvents." **9**(2): 930-938.

Najafpoor, A., R. Norouzian-Ostad, H. Alidadi, T. Rohani-Bastami, M. Davoudi, F. Barjasteh-Askari and J. Zanganeh (2020). "Effect of magnetic nanoparticles and silver-loaded magnetic nanoparticles on advanced wastewater treatment and disinfection." Journal of Molecular Liquids **303**: 112640.

Nel, A., T. Xia, L. Mädler and N. Li (2006). "Toxic potential of materials at the nanolevel." science **311**(5761): 622-627.

Oki, T. and S. Kanae (2006). "Global hydrological cycles and world water resources." science **313**(5790): 1068-1072.

Olvera, R. C., S. L. Silva, E. Robles-Belmont and E. Z. Lau (2017). "Review of nanotechnology value chain for water treatment applications in Mexico." Resource-Efficient Technologies **3**(1): 1-11.

Pan, B., B. Pan, W. Zhang, L. Lv, Q. Zhang and S. Zheng (2009). "Development of polymeric and polymer-based hybrid adsorbents for pollutants removal from waters." Chemical Engineering Journal **151**(1-3): 19-29.

Pandi, K., S. M. Prabhu, Y. Ahn, C. M. Park and J. Choi (2020). "Design and synthesis of biopolymer-derived porous graphitic carbon covered iron-organic frameworks for depollution of arsenic from waters." Chemosphere **254**: 126769.

Pang, Y., Y. Ruan, Y. Feng, Z. Diao, K. Shih, D. Chen and L. J. C. Kong (2019). "Ultrasound assisted zero valent iron corrosion for peroxymonosulfate activation for Rhodamine-B degradation." **228**: 412-417.

Ponce-Rodríguez, H., J. Verdú-Andrés, R. Herráez-Hernández and P. Campíns-Falcó (2020). "Exploring hand-portable nano-liquid chromatography for in place water analysis: Determination of trimethylxanthines as a use case." Science of The Total Environment **747**: 140966.

Pradeep, T. (2009). "Noble metal nanoparticles for water purification: a critical review." Thin solid films **517**(24): 6441-6478.

Qiu, M., Z. Liu, S. Wang and B. Hu (2021). "The photocatalytic reduction of U (VI) into U (IV) by ZIF-8/g-C3N4 composites at visible light." Environmental Research **196**: 110349.

Rambabu, K., G. Bharath, F. Banat and P. L. J. J. o. h. m. Show (2021). "Green synthesis of zinc oxide nanoparticles using Phoenix dactylifera waste as bioreductant for effective dye degradation and antibacterial performance in wastewater treatment." **402**: 123560.

Ray, P. C., H. Yu and P. P. Fu (2009). "Toxicity and environmental risks of nanomaterials: challenges and future needs." Journal of Environmental Science and Health Part C **27**(1): 1-35.

Ren, S., J. Tao, F. Tan, Y. Cui, X. Li, J. Chen, X. He and Y. Wang (2018). "Diffusive gradients in thin films based on MOF-derived porous carbon binding gel for in-situ measurement of antibiotics in waters." Science of the total environment **645**: 482-490.

Rico-Oller, B., A. Boudjemaa, H. Bahruji, M. Kebir, S. Prashar, K. Bachari, M. Fajardo and S. Gómez-Ruiz (2016). "Photodegradation of organic pollutants in water and green hydrogen production via methanol photoreforming of doped titanium oxide nanoparticles." Science of the Total Environment **563**: 921-932.

Rubilar, R., R. Hubbard, V. Emhart, O. Mardones, J. J. Quiroga, A. Medina, H. Valenzuela, J. Espinoza, Y. Burgos and D. Bozo (2020). "Climate and water availability impacts on early growth and growth efficiency of Eucalyptus genotypes: The importance of GxE interactions." Forest Ecology and Management **458**: 117763.

Rupa, E. J., G. Anandapadmanaban, M. Chokkalingam, J. F. Li, J. Markus, V. Soshnikova, Z. Perez and D.-C. Yang (2019). "Cationic and anionic dye degradation activity of Zinc oxide nanoparticles from Hippophae rhamnoides leaves as potential water treatment resource." Optik **181**: 1091-1098.

Sahoo, S. K., G. K. Panigrahi, A. Sahoo, A. K. Pradhan and A. Dalbehera (2021). "Bio-hydrothermal synthesis of ZnO–ZnFe2O4 nanoparticles using Psidium guajava leaf extract: Role in waste water remediation and plant immunity." Journal of Cleaner Production **318**: 128522.

Satheesh, R., K. Vignesh, M. Rajarajan, A. Suganthi, S. Sreekantan, M. Kang and B. S. Kwak (2016). "Removal of congo red from water using quercetin modified α-Fe2O3 nanoparticles as effective nanoadsorbent." Materials Chemistry and Physics **180**: 53-65.

Shah, A. I., M. U. D. Dar, R. A. Bhat, J. Singh, K. Singh and S. A. Bhat (2020). "Prospectives and challenges of wastewater treatment technologies to combat contaminants of emerging concerns." Ecological Engineering **152**: 105882.

Shen, J., W. Huang, N. Li and M. Ye (2015). "Highly efficient degradation of dyes by reduced graphene oxide–ZnCdS supramolecular photocatalyst under visible light." Ceramics International **41**(1): 761-767.

Shkir, M., B. M. Al-Shehri, M. Pachamuthu, A. Khan, K. V. Chandekar, S. AlFaify and M. S. Hamdy (2020). "A remarkable improvement in photocatalytic activity of ZnO nanoparticles through Sr doping synthesized by one pot flash combustion technique for water treatments." Colloids and Surfaces A: Physicochemical and Engineering Aspects **587**: 124340.

Sholl, D. and R. Lively (2016). "Seven chemical separations to change the world (vol 532, pg 435, 2016)." Nature **533**(7603): 316-316.

Singh, J., S. Juneja, R. Soni and J. Bhattacharya (2021). "Sunlight mediated enhanced photocatalytic activity of TiO2 nanoparticles functionalized CuO-Cu2O nanorods for removal of methylene blue and oxytetracycline hydrochloride." Journal of Colloid and Interface Science **590**: 60-71.

Sitko, R., B. Zawisza and E. Malicka (2013). "Graphene as a new sorbent in analytical chemistry." TrAC Trends in Analytical Chemistry **51**: 33-43.

Soares, S. F., T. R. Simões, M. António, T. Trindade and A. L. Daniel-da-Silva (2016). "Hybrid nanoadsorbents for the magnetically assisted removal of metoprolol from water." Chemical Engineering Journal **302**: 560-569.

Solis, K. L. B., Y.-H. Kwon, M.-H. Kim, H.-R. An, C. Jeon and Y. Hong (2020). "Metal organic framework UiO-66 and activated carbon composite sorbent for the concurrent adsorption of cationic and anionic metals." Chemosphere **238**: 124656.

Srivastav, A. L., N. Patel and V. K. Chaudhary (2020). "Disinfection by-products in drinking water: Occurrence, toxicity and abatement." Environmental Pollution: 115474.

Su, C., Q. Ru, S. Cheng, Y. Gao, F. Chen, L. Zhao and F. C.-C. Ling (2019). "3D pollen-scaffolded NiSe composite encapsulated by MOF-derived carbon shell as a high-low temperature anode for Na-ion storage." Composites Part B: Engineering **179**: 107538.

Tabushi, I., Y. Kobuke and T. Nishiya (1979). "Extraction of uranium from seawater by polymer-bound macrocyclic hexaketone." Nature **280**(5724): 665-666.

Taju, G., S. A. Majeed, K. Nambi and A. S. Hameed (2014). "In vitro assay for the toxicity of silver nanoparticles using heart and gill cell lines of Catla catla and gill cell line of Labeo rohita." Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology **161**: 41-52.

Takahashi, H., Y. Niidome, T. Niidome, K. Kaneko, H. Kawasaki and S. Yamada (2006). "Modification of gold nanorods using phosphatidylcholine to reduce cytotoxicity." Langmuir **22**(1): 2-5.

Tan, W., Y. Ruan, Z. Diao, G. Song, M. Su, D. Chen, L. Kong and H. J. C. Deng (2021). "Removal of levofloxacin through adsorption and peroxymonosulfate activation using carbothermal reduction synthesized nZVI/carbon fiber." **280**: 130626.

Tang, J. and J. Wang (2020). "Iron-copper bimetallic metal-organic frameworks for efficient Fenton-like degradation of sulfamethoxazole under mild conditions." Chemosphere **241**: 125002.

Tang, Y., X. Long, M. Wu, S. Yang, N. Gao, B. Xu and S. Dutta (2020). "Bibliometric Review of Research Trends on Disinfection By-Products in Drinking Water during 1975-2018." Separation and Purification Technology: 116741.

Thostenson, E. T., Z. Ren and T.-W. Chou (2001). "Advances in the science and technology of carbon nanotubes and their composites: a review." Composites science and technology **61**(13): 1899-1912.

Tiede, K., A. B. Boxall, S. P. Tear, J. Lewis, H. David and M. Hassellöv (2008). "Detection and characterization of engineered nanoparticles in food and the environment." Food additives and contaminants **25**(7): 795-821.

Tiwari, J. N., K. Mahesh, N. H. Le, K. C. Kemp, R. Timilsina, R. N. Tiwari and K. S. Kim (2013). "Reduced graphene oxide-based hydrogels for the efficient capture of dye pollutants from aqueous solutions." Carbon **56**: 173-182.

Vasantharaj, S., P. Shivakumar, S. Sathiyavimal, P. Senthilkumar, S. Vijayaram, M. Shanmugavel and A. Pugazhendhi (2021). "Antibacterial activity and photocatalytic dye degradation of copper oxide nanoparticles (CuONPs) using Justicia gendarussa." Applied Nanoscience.

Verma, B. and C. Balomajumder (2020). "Surface modification of one-dimensional Carbon Nanotubes: A review for the management of heavy metals in wastewater." Environmental Technology & Innovation **17**: 100596.

Wadhawan, S., A. Jain, J. Nayyar and S. K. Mehta (2020). "Role of nanomaterials as adsorbents in heavy metal ion removal from waste water: A review." Journal of Water Process Engineering **33**: 101038.

Wang, C., H. Shi, P. Zhang and Y. Li (2011). "Synthesis and characterization of kaolinite/TiO2 nano-photocatalysts." Applied Clay Science **53**(4): 646-649.

Wang, H., Q. Zhang, M. Qiu and B. Hu (2021). "Synthesis and application of perovskite-based photocatalysts in environmental remediation: A review." Journal of Molecular Liquids: 116029.

Wang, J., X. Tang, Y. Xu, X. Cheng, G. Li and H. Liang (2020). "Hybrid UF/NF process treating secondary effluent of wastewater treatment plants for potable water reuse: Adsorption vs. coagulation for removal improvements and membrane fouling alleviation." Environmental Research **188**: 109833.

Wang, J., S. Zhang, B. Pan, W. Zhang and L. Lv (2011). "Hydrous ferric oxide–resin nanocomposites of tunable structure for arsenite removal: Effect of the host pore structure." Journal of hazardous materials **198**: 241-246.

Wang, S., C. W. Ng, W. Wang, Q. Li and L. Li (2012). "A comparative study on the adsorption of acid and reactive dyes on multiwall carbon nanotubes in single and binary dye systems." Journal of Chemical & Engineering Data **57**(5): 1563-1569.

Wang, W., F. Lin, B. Yan, Z. Cheng, G. Chen, M. Kuang, C. Yang and L. Hou (2020). "The role of seashell wastes in TiO2/Seashell composites: Photocatalytic degradation of methylene blue dye under sunlight." Environmental Research **188**: 109831.

Wei, H., S. Deng, Q. Huang, Y. Nie, B. Wang, J. Huang and G. Yu (2013). "Regenerable granular carbon nanotubes/alumina hybrid adsorbents for diclofenac sodium and carbamazepine removal from aqueous solution." Water research **47**(12): 4139-4147.

Wong, J. K. H., H. K. Tan, S. Y. Lau, P.-S. Yap and M. K. Danquah (2019). "Potential and challenges of enzyme incorporated nanotechnology in dye wastewater treatment: A review." Journal of environmental chemical engineering **7**(4): 103261.

Wu, W., Y. Shi, G. Liu, X. Fan and Y. Yu (2020). "Recent development of graphene oxide based forward osmosis membrane for water treatment: A critical review." Desalination **491**: 114452.

Xiong, Z., L. L. Zhang, J. Ma and X. Zhao (2010). "Photocatalytic degradation of dyes over graphene–gold nanocomposites under visible light irradiation." Chemical Communications **46**(33): 6099-6101.

Xu, J., Z. Cao, Y. Zhang, Z. Yuan, Z. Lou, X. Xu and X. Wang (2018). "A review of functionalized carbon nanotubes and graphene for heavy metal adsorption from water: Preparation, application, and mechanism." Chemosphere **195**: 351-364.

Yadav, A., P. Chowdhary, G. Kaithwas and R. Bharagava (2017). "Toxic metals in environment, threats on ecosystem and bioremediation approaches." Handbook of metalmicrobe interactions and bioremediation. CRC Press, Taylor & Francis Group, Boca Raton **813**.

Yang, C.-H., J.-S. Chang and D.-J. Lee (2020). "Covalent organic framework EB-COF: Br as adsorbent for phosphorus (V) or arsenic (V) removal from nearly neutral waters." Chemosphere **253**: 126736.

Yang, S., J. Hu, C. Chen, D. Shao and X. Wang (2011). "Mutual effects of Pb (II) and humic acid adsorption on multiwalled carbon nanotubes/polyacrylamide composites from aqueous solutions." Environmental science & technology **45**(8): 3621-3627.

Yang, X., N. Guo, Y. Yu, H. Li, H. Xia and H. Yu (2020). "Synthesis of magnetic graphene oxide-titanate composites for efficient removal of Pb (II) from wastewater: Performance and mechanism." Journal of environmental management **256**: 109943.

Yang, Y., Y. Xie, L. Pang, M. Li, X. Song, J. Wen and H. Zhao (2013). "Preparation of reduced graphene oxide/poly (acrylamide) nanocomposite and its adsorption of Pb (II) and methylene blue." Langmuir **29**(34): 10727-10736.

Yin, Z., C. Cui, H. Chen, X. Yu and W. Qian (2020). "The Application of Carbon Nanotube/Graphene-Based Nanomaterials in Wastewater Treatment." Small **16**(15): 1902301.

Yu, J.-G., D.-S. Huang, K.-L. Huang and Y. Hong (2011). "Cross-linking of multi-walled carbon nanotubes with polyethylene glycol." Polymer-Plastics Technology and Engineering **50**(3): 328-331.

Yu, Y., C. Y. Jimmy, C.-Y. Chan, Y.-K. Che, J.-C. Zhao, L. Ding, W.-K. Ge and P.-K. Wong (2005). "Enhancement of adsorption and photocatalytic activity of TiO2 by using carbon nanotubes for the treatment of azo dye." Applied Catalysis B: Environmental **61**(1-2): 1-11.

Yuan, Y., B. Niu, Q. Yu, X. Guo, Z. Guo, J. Wen, T. Liu, H. Zhang and N. Wang (2020). "Photoinduced multiple effects to enhance uranium extraction from natural seawater by black phosphorus nanosheets." Angewandte Chemie International Edition **59**(3): 1220-1227.

Yuan, Y., Q. Yu, J. Wen, C. Li, Z. Guo, X. Wang and N. Wang (2019). "Ultrafast and Highly Selective Uranium Extraction from Seawater by Hydrogel-like Spidroin-based Protein Fiber." Angewandte Chemie **131**(34): 11911-11916.

Zhang, H., Y. Ruan, A. Liang, K. Shih, Z. Diao, M. Su, D. Chen, H. Lu and L. J. J. o. C. P. Kong (2019). "Carbothermal reduction for preparing nZVI/BC to extract uranium: Insight into the iron species dependent uranium adsorption behavior." **239**: 117873.

Zhang, N., Y. Zhang, X. Pan, M.-Q. Yang and Y.-J. Xu (2012). "Constructing ternary CdS–graphene–TiO_2 hybrids on the flatland of graphene oxide with enhanced visible-light photoactivity for selective transformation." The Journal of Physical Chemistry C **116**(34): 18023-18031.

Zhang, Y., H. Chi, W. Zhang, Y. Sun, Q. Liang, Y. Gu and R. Jing (2014). "Highly efficient adsorption of copper ions by a PVP-reduced graphene oxide based on a new adsorptions mechanism." Nano-Micro Letters **6**(1): 80-87.

Zhou, Z., W. Zhong, K. Cui, Z. Zhuang, L. Li, L. Li, J. Bi and Y. Yu (2018). "A covalent organic framework bearing thioether pendant arms for selective detection and recovery of Au from ultra-low concentration aqueous solution." Chemical Communications **54**(71): 9977-9980.

Zhu, H., R. Jiang, Y.-Q. Fu, J.-H. Jiang, L. Xiao and G.-M. Zeng (2011). "Preparation, characterization and dye adsorption properties of γ-Fe_2O_3/SiO_2/chitosan composite." Applied Surface Science **258**(4): 1337-1344.

Zhu, Y., S. Murali, W. Cai, X. Li, J. W. Suk, J. R. Potts and R. S. Ruoff (2010). "Graphene and graphene oxide: synthesis, properties, and applications." Advanced materials **22**(35): 3906-3924.

Zou, R., Z. Zhang, L. Yu, Q. Tian, Z. Chen and J. Hu (2011). "A general approach for the growth of metal oxide nanorod arrays on graphene sheets and their applications." Chemistry–A European Journal **17**(49): 13912-13917.