



REVIEW ARTICLE

Adsorption of thallium from wastewater using disparate nano-based materials: A systematic review



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Abstract Development of promising technologies to remove thallium as a highly poisonous contaminant is of great attention to guarantee the sustainable supplement of safe potable water and human well-being all around the world. Recently, adsorption has been introduced as a noteworthy technique to remove trace amount of thallium. In the past, the rate of thallium removal using the adsorption technique was relatively low due to the fact that this method was significantly influenced by the co-existing cations. To overcome this problem, more promising adsorbents such as nano-based materials have been developed. These adsorbents have shown great potential in the process of thallium removal due to their large surface area and superior selectivity. The main objective of this paper is to present a state-of-the-art review about the potential of nano-based form of disparate materials (i.e., titanium compounds, MnO₂, ZnO, Al₂O₃ and multiwall carbon nanotubes) to separate thallium from water/waste water sources. Then, a systematic overview about acute/chronic toxicities of thallium for humans is aimed to be provided. Throughout the review, the authors aim to compare the negative and positive aspects of each treatment technique and offer promising

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technologies for thallium removal. At the end, an outlook on the recent advancements in the adsorption process of thallium using nanomaterials is provided.

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1. Introduction

Separation and removal of impurities from water and wastewater streams is of vital importance from environmental point of view. These impurities could be in different forms such as microbial, ions, organic molecules, etc. (He, 2021; Ni et al., 2021; Yang et al., 2020; Moondra et al., 2021; Chen et al., 2018; Zhao, 2020; Yang et al., 2021; Handschuh Wang et al., 2021; Liu et al., 2020). Among various elements which exist in wastewater, thallium (Tl) is a scarce element, which its high dispersion in the environment has caused it to be prioritized as an important contaminant by the U.S. Environmental Protection Agency (USEPA) (EPAToxic, U., Toxic and Priority

Pollutants Under the Clean Water Act. US EPA available online: <https://www.epa.gov/eg/toxic-and-priority-pollutants-under-clean-water-act> (accessed on 24 January 2021; Xu, 2019; Aslam et al., 2021). This rare metal, which was discovered in 1861, is of paramount importance in different industries such as chemical, pharmaceutical, aerospace and superconducting materials (Belzile and Chen, 2017; Liu et al., 2019; Babanezhad et al., 2020).

Apart from various applications of thallium in industrial-based activities, this metal has shown extreme toxicity on humans' body even more than mercury, lead and cadmium (Babanezhad et al., 2020; ZITKO, 1975; Li, 2020). The fatal dose of thallium for adults is just 8–10 mg.kg⁻¹ but the uptake

H																	He																												
Li	Be											B	C	N	O	F	Ne																												
Na	Mg											Al	Si	P	S	Cl	Ar																												
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr																												
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe																												
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<table border="1"> <tr> <td>Ce</td> <td>Pr</td> <td>Nd</td> <td>Pm</td> <td>Sm</td> <td>Eu</td> <td>Gd</td> <td>Tb</td> <td>Dy</td> <td>Ho</td> <td>Er</td> <td>Tm</td> <td>Yb</td> <td>Lu</td> </tr> <tr> <td>Th</td> <td>Pa</td> <td>U</td> <td>Np</td> <td>Pu</td> <td>Am</td> <td>Cm</td> <td>Bk</td> <td>Cf</td> <td>Es</td> <td>Fm</td> <td>Md</td> <td>No</td> <td>Lr</td> </tr> </table>																		Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
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Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr																																

Fig. 1 The exact location of thallium in the Periodic Table of the Elements (ETF).

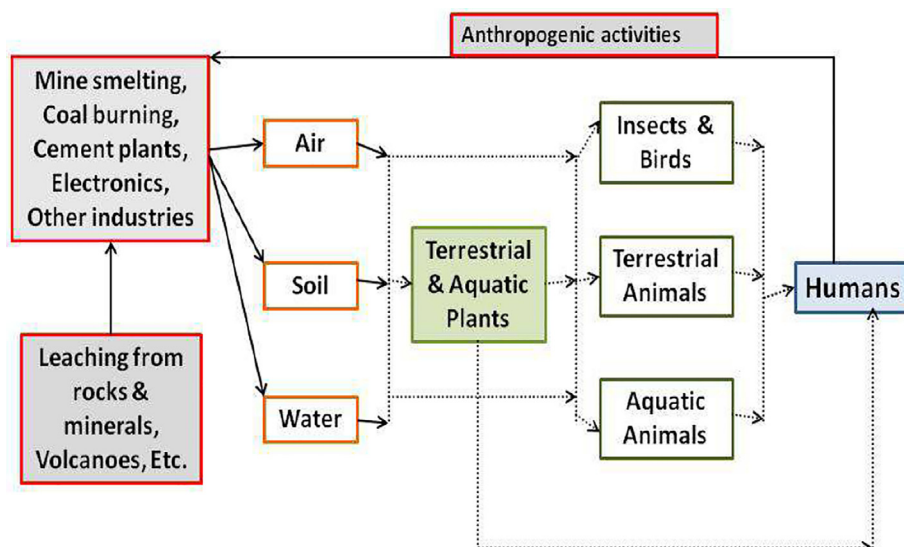


Fig. 2 Simplified illustration of thallium cycle in the environment. Reprinted from (Belzile and Chen, 2017) with permission from Elsevier.

of even much lower dose by humans' body may cause adverse acute/chronic poisoning with various symptoms such as vomiting, diarrhea, hair loss and kidney/liver failure (Birungi and Chirwa, 2015; Puccini et al., 2018; Osorio-Rico et al., 2017; Li, 2019; Marjani, 2021). Adsorption has shown to be a promising technology for removal of various pollutants such as thallium from water and wastewater effluents (Chen, 2021; He, 2021; Moondra, 2021; Shi, 2021; Wang, 2021; Wong, 2017; Yang, 2020, 2021; Zhang, 2020, 2021; Yang et al., 2020). Adsorption is based on separation and mass transfer between a solution and solid phase. Various adsorbents have been synthesized by chemical and physical techniques for efficient removal of ions and organic molecules from water streams (Cao et al., 2021; Chen, 2018; Feng, 2020; Guan, 2020; Han, 2021; Handschuh

Wang, 2021; He, 2021; Lin, 2019; Liu, 2020). Beside adsorption separation process, membrane separation technology has shown to be efficient in removal of ions and organic matters from water by which the separation can be driven mainly by pressure, electrical, temperature, or concentration gradient (Böning et al., 2018; Wick et al., 2018).

Thallium has very low solubility in alkali and liquid ammonia, but it possesses significant solubility in nitric acid. The reaction rate of thallium with dilute sulfuric acid is much lower than dilute nitric acid. This rare element with the atomic number 81 belongs to the thirteenth group of the Periodic Table of the Elements can be present in two oxidation states including Tl(I) and Tl(III), which demonstrates different chemistry in aqueous media. Monovalent thallium possesses more thermodynamic sta-

Table 1 Comprehensive information about different employed techniques to remove thallium from water/wastewater sources.

Removal technique	Advantages	Disadvantages	Ref.
Chemical precipitation	<ul style="list-style-type: none"> • Efficacious for industrial waste water with high salinity • Easy procedure • Extensive application • Appropriate for large scale treatment 	<ul style="list-style-type: none"> • Sludge production • Slight metal precipitation • Weak settlement • Generation of secondary contaminants such as acid gas 	(Liu et al., 2019; Chen et al., 2013; Li et al., 2017; Yang et al., 2017)
Ion exchange	<ul style="list-style-type: none"> • Simplicity of operation • High removal efficiency • High Capability of recovering precious metals • Low sludge generation • High selectivity 	<ul style="list-style-type: none"> • High operational costs • Disability of application in large scale • Resin fouling • Generation of secondary contaminant 	(Vincent et al., 2014)
Solvent extraction	<ul style="list-style-type: none"> • Excellent selectivity • High removal performance 	<ul style="list-style-type: none"> • Significant use of chemicals • Production of organic waste 	(Wan et al., 2014)
Adsorption	<ul style="list-style-type: none"> • Negligible fouling • Simplicity of operation, • Excellent efficiency • Affordability 	<ul style="list-style-type: none"> • Sludge generation • Enhanced risk of nano-pollutants generation 	(Ussipbekova, 2015. 2015.; Li et al., 2017; Huangfu et al., 2015; Tian et al., 2017; Wang et al., 2018)
Biotechnology	<ul style="list-style-type: none"> • Coupling with electricity generation 	<ul style="list-style-type: none"> • Not appropriate for high thallium concentrations • Requirement of more development 	(Wang, 2020; Marjani et al., 2020)
Electrocoagulation	<ul style="list-style-type: none"> • Great economical affordability • Significant eco-friendliness 	<ul style="list-style-type: none"> • Sludge production 	(Agency, 2002)

bility, which makes it the governing thallium species in environment (Belzile and Chen, 2017; Liu et al., 2014; Li et al., 2019; Antonia López Antón et al., 2013; Li, 2020). Fig. 1 shows the exact location of thallium in the Periodic Table of the Elements.

Due to the existence of numerous dispersion sources to nature along with great solubility in aqueous environment, thallium compounds has been recently considered to have potential harms to humans' potable water or food chain (Babanezhad et al., 2020; Li et al., 2018; Li et al., 2018; Li et al., 2017; Hosseini and Hassan-Abadi, 2008). Fig. 2 renders a simplified cycle of thallium in the environment. Therefore, thallium removal from wastewater seems to be vital to mitigate its deleterious impacts on human well-being. In last decades, several techniques such as precipitation, flotation, electrochemical deposition, ion exchange and solvent extraction have been emerged to separate thallium from water/waste water sources (Ussipbekova, 2015. 2015.; Escudero et al., 2013; Nabipour et al., 2020; xxxx; Twidwell and Williams-Beam, 2002). Table 1 gives detailed information about the performance of disparate employed techniques to remove thallium from water/wastewater sources.

Despite the variety of existed techniques, very few of them have shown their potential of application in industries due to the fact that the abovementioned procedures often have some drawbacks such as low performance, production of large scale of waste and high energy consumption (Ghadiri et al., 2020; Ecer and Şahan, 2018; Zhao, 2020). Recently, adsorption has shown appropriate potential for use in industrial-based wastewater processing for thallium removal due to having important privileges such as great purification performance, low energy consumption, and eco-friendly characteristics (Yang, 2019). Some efficient and promising adsorbents such as Prussian blue analogues, biosorbents and metal oxides have been synthetically investigated to evaluate their efficiency to separate trace amount Tl (I) from wastewater (Kumar et al., 2015).

In recent decades, nano-based substances have been identified as an appropriate approach to separate heavy/poisonous metals from various types of surface/ underground wastewater sources. Over the past decades, nano-based adsorbents have

achieved numerous attentions (Liang et al., 2005; Ni et al., 2021; Yang, 2021; Yap et al., 2017; Zhang, 2020; Zhao, 2020). In various scientific fields such as wastewater treatment, health care, membrane-based separation process and energy due to illustrating numerous noteworthy properties including high surface area and small size/quantum effect (Pishnamazi, 2020; Pishnamazi et al., 2020; Shirazian, 2020; Cao, 2021; Pumera, 2011; Marjani, 2020; Yinghua et al., 2006; Nguyen et al., 2020; Vunain et al., 2016). These positive characteristics are due to their brilliant adsorption capacity and reactivity, which are desirable for heavy/poisonous metals removal (Yaqoob, 2020; Karthigadevi, 2021; Pishnamazi, 2020; Babanezhad et al., 2021; Nnaji, 2018). Despite the abovementioned advantages, high cost and time-consuming processes are considered as the main disadvantages of nano-based materials, which have confined their application for heavy/poisonous metals removal (Babanezhad et al., 2020; Williams-Beam and Twidwell, 2003; Zhang et al., 2018).

This paper presents a state-of-the-art review about the feasibility of various sorts of nano-based materials to separate thallium from disparate water/waste water sources. Then, a systematic overview about the acute/chronic toxicities of thallium for humans is aimed to be provided. Investigation of several feasible nano-based materials towards thallium separation is another aim of this paper. Throughout the review, the authors aim to compare the advantages and disadvantages of each treatment technique and offer promising technologies for thallium removal. Ultimately, an outlook on the recent advancements in the adsorption process of thallium using nanomaterials is provided.

2. Standard amount of thallium in water/wastewater sources

Global environmental standards are regulated to evaluate the effects of various human-based pollutants on the environment and consequently the ecosystem's protection from their abnormal dispersion/emission. Standards for water pollutant discharge (SWPD) specify the highest amounts of contaminants discharged by human-based water pollution sources to gain

Table 2 Standards for thallium in water/wastewater sources.

Classification	Source/Agency	Limited value ($\mu\text{g.L}^{-1}$)	Ref.
Water quality standard	Water + organism/USEPA	0.24	(Deng et al., 2016)
	Organism only/USEPA	0.47	(Deng et al., 2016)
	Drinking water, maximum contaminant level goal (MCLG)/USEPA	0.5	(CCME, 2002)
	Drinking water, maximum contaminant level (MCL)/USEPA	2	(CCME, 2002)
	Sea water/USEPA	4	(China, GB3838-2002, 2002.)
	Fresh water/Canada	0.8	(Jin, et al., 2006)
	Water quality/China	0.1	(MH, S., Standards for drinking water quality (GB 5749-, 2006)
	Drinking water/China	0.1	(Rosengrant and Craig, 1990; Flegal and Patterson, 1985)
Discharge standard of contaminants	Best demonstrated available technology (BDAT) for thallium wastewater/U.S.A	140	(Cheam, 2001)
	Inorganic chemical industry/China	5	(Xu, 2019)
	Industrial wastewater in Hunan province/China	5	(Xu, 2019; Liu et al., 2019)

appropriate water quality standards (Xu, 2019; National Primary Drinking Water Regulations: Thallium (Technical Version)., 1995). Detailed summarization of the environmental standards for toxic element of thallium in water and wastewater is presented in Table 2. The USEPA notifies the fact that the most efficient current technologies (TMECTs) must decrease the thallium concentration to lower than 140 mg.L^{-1} . However, in China where the pollution of water sources with thallium is more serious, stricter standards for thallium discharge are stipulated. According to their standards, the thallium concentration should be less than 5 mg mg.L^{-1} and decreased to less than 2 mg.L^{-1} after 2020 (Xu, 2019).

3. Existence of thallium in natural waters

To the base of the author's knowledge, little is known about the fate of thallium in the aquatic environments. In fact, before the current years, the detection of thallium in water sources was extremely difficult (Cheam et al., 1995). Accurate evaluations of the recent years have illustrated that the amount of dissolved thallium concentrations in seawater, unpolluted and polluted freshwater is $10\text{--}15$, $5\text{--}10$ and $20\text{--}50 \text{ ng.L}^{-1}$, respectively (Peter and Viraraghavan, 2005; Shand et al., 1998; Wallwork-Barber et al., 1985). Flegal et al. concluded that the thallium concentrations in phytoplankton, zooplankton and ichthyoplankton from the central pacific ocean were $0.02\text{--}0.8$, $0.03\text{--}0.5$ and $0.1 \text{ attogram.liter}^{-1}$ (ag.L^{-1}), respectively (Cheam et al., 1995). The data obtained showed that the thallium concentration in seawater is approximately constant. Thallium was investigated in surface waters gathered from low-order upland streams from an extensive variety of sedimentary/igneous/metamorphic rock sorts. It was perceived the value of thallium in the majority of surface waters was lower than the detection limit but high value of thallium (up to 490 ng.L^{-1}) was found in waters near to auriferous ore bodies (Gramlich et al., 2001). Thallium concentrations through river-/ground water have been reported 0.04 ag.L^{-1} and 800 ag.L^{-1} , respectively. Certain transport of thallium took place through water, fish and plants but there isn't any substantial thallium transport between sand and other ecosystem components (Šidlo et al., 2021).

Tl (III) ion- 4-(2-pyridylazo) re-sorcinol (PAR) azodye ligand builds complexes of 1:1 and 1:2 stoichiometry. The concentration of this complex in solution relies on a number of important parameters including pH and ligand–metal ion ratio. At pH values greater than 3, the formation of 1:2 complex takes place quantitatively whereas the formation of 1:1 complex can be seen at pH values around 1 (Musso, 1993; Chen et al., 2000). Due to the intervention of prevalent buffers with high concentration (more than 0.05 M) of Tl(III) complex formation, the acetate buffer (with the concentration 0.01 M) was applied to regulate the pH value around 4 to hinder the feasible reduction of Tl^{3+} to Tl^{+} in presence of halide X^{-} (Cvjetko et al., 2010; Rickwood et al., 2015).

4. Acute and chronic toxicity of thallium for humans

Vomiting, diarrhea, hair loss and serious failure in the functions of kidneys/hear/lungs can be considered as the serious toxicity of the large-amounts ingestion of thallium over a short period of time from (Osorio-Rico et al., 2017). The major characteristics of acute thallium toxicity on humans are gastrointestinal disorders, polyneuropathy, alopecia, acne and anhydrosis (Wallwork-Barber et al., 1985; Manikandan, 2020; Elveny, 2021; Merian and Clarkson, 1991; Nakhjiri and Roudsari, 2016). It is worth noting that the central/peripheral nervous system is the major human-related organ damaged by abnormal exposure of thallium. Of course, the severity of symptoms significantly depends on age, dosage and administration procedure (Nakhjiri and Heydarinasab, 2020; Riyaz et al., 2013; Ramsden, 2002).

In the case of chronic symptoms, the 350 years history of thallium mining in several countries has led to the appearance of disproportionate symptoms of chronic thallium poisoning such as anorexia, abdominal pain, blindness and even death in the extreme condition (Becking and Chen, 1998). White streaks might be appeared on finger-/toe nails if the long-term absorption of thallium takes place (Manikandan, 2020; Hoffman and Hoffman, 2000). Despite the limited information available on the impacts of thallium on human reproduction, some literatures have reported adverse effects such as menstrual cycle imbalance and sperm inadequacy (Nuvolone,

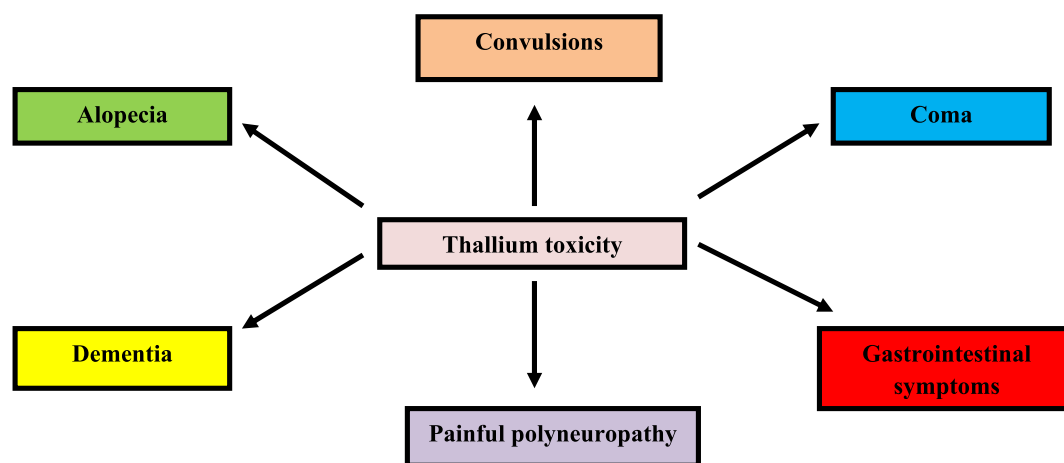


Fig. 3 Important acute/chronic adverse effects of thallium on the humans' health. Reprinted from (Singh et al., 2020) with permission from Elsevier.

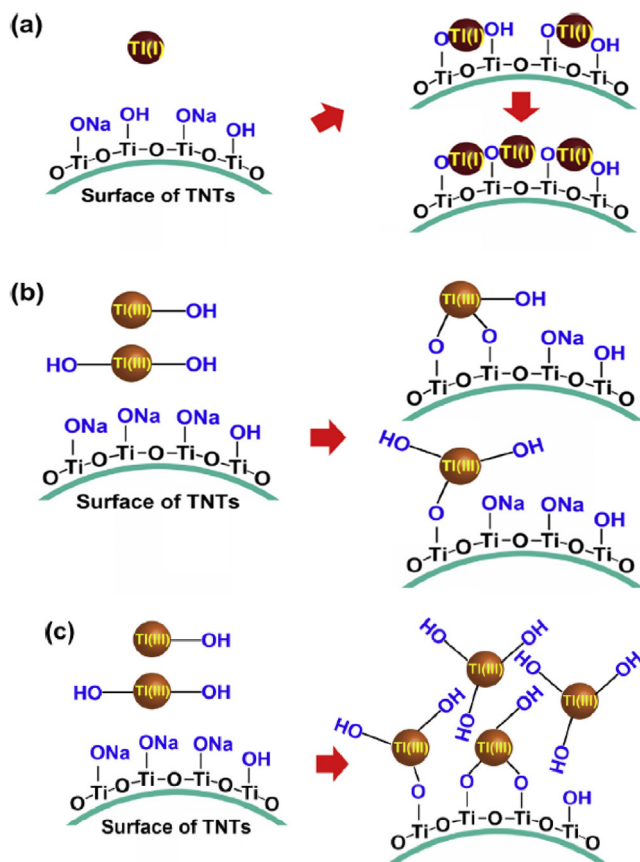


Fig. 4 Schematic illustration of (a) Ti(I) and (b), (c) Ti(III) adsorption mechanisms applying TNTs. Reprinted from (Liu et al., 2014) with permission from Elsevier.

2021; Singh et al., 2020; Zhang, 2009). Some major acute/chronic adverse effects of thallium on the humans' health are illustrated in Fig. 3.

5. Common nano-based materials for thallium adsorption

5.1. Titanium compounds

Titanium compounds including titanium dioxide nanoparticles (TiO₂NPs), titanium dioxide (TiO₂), titanate nanotubes (TNTs) and titanium peroxide (TiPO) are the first classification of adsorption materials, which is comprehensively scrutinized in this paper. It has been analytically reported that TiO₂ nanoparticles possess great capability to remove thallium from water/wastewater sources with the maximum adsorption capacity of 258 mg.g⁻¹ (Li et al., 2017). In recent years, TNTs and TiPO have received the most attention due to their brilliant capabilities, such as greater adsorption capacity and strong selectivity to remove thallium from water/wastewater sources (Antonia López Antón et al., 2013; Li et al., 2017). Despite significant positive characteristics for thallium removal, the regeneration by titanium peroxide is described as very difficult (Li et al., 2017). Zhang et al. concluded that the regeneration process of TiPO through HNO₃ is entirely impossible due to the existence of strong affinity between Ti (I) and the surface of adsorbent (Li et al., 2017). The adsorption of Ti (III) applying TiO₂NPs and TNTs have recently

been under consideration. TNTs have demonstrated a superior adsorption capacity for Ti (III) compared to TiO₂NPs (388.3 mg.g⁻¹ vs 24.09 mg.g⁻¹) (Antonia López Antón et al., 2013; Zhang, 2008). Fig. 4 schematically illustrates the adsorption mechanisms of Ti (I) and Ti (III) using TNTs.

5.2. Al₂O₃ nanoparticles

Currently, Al₂O₃ nanoparticles (Al₂O₃NPs) have been introduced as a promising adsorbent to remove thallium from aqueous solution. At present, nanoparticles are promising functional materials of great interest owing to their noteworthy properties. Due to the unsaturated nature of nanoparticles on the surface of the most atoms, they are capable of binding to other atoms easily. Nanoparticles possess significant adsorption capacity, easy operation and fast adsorption process and therefore, it could be operationally applied as adsorbents (Mahdavi et al., 2013; Martel et al., 1998). It has been shown experimentally that Al₂O₃NPs are significantly effective for the adsorption of Ti (III) from aqueous solutions such as water/wastewater sources. To put the issue into the perspective view, Al₂O₃NPs can remove almost all of the existed Ti (III) from solution at pH 4.5 (Martel et al., 1998; Hrapovic et al., 2004). Fig. 6 schematically illustrates the molecular structure of Al₂O₃NPs.

5.3. Multiwall carbon nanotubes (MWCNTs)

Carbon nanotubes (CNTs) have been extensively used in disparate applications such as electronic transistors, biosensors, gas separation and optical component because of their brilliant chemical, mechanical and electronic characteristics (Ramsden, 2002; Liu et al., 2012; Pishnamazi et al., 2020; Edgington et al., 2010; Bai et al., 2010). However, rapid advances in the production and industrial uses of CNTs can render incidental exposure to human/environment receptors (Klaine, 2008; Wang et al., 2010; Pu et al., 2013). Due to their large surface area, CNTs has the ability of altering the destiny, transmission and bioaccessibility of pollutants by powerful adsorptive interactions (Zhang et al., 2011; Sheng, 2010). By elapsing the time, Ti (I) and disparate types of CNTs are likely to emerge in the aquatic environment. Despite an extensive study of the adsorption process of numerous pollutants (i.e., heavy metals) in CNTs, very little research have been implemented to evaluate the interaction mechanisms of Ti (I) -CNT. Owing to the fact that the modification of surface may considerably increase colloidal consistency of CNTs and consequently affects adsorption performance, the dynamism of Ti(I) related to the modified surface of CNTs might be changed in environment (Zhang et al., 2011; Yu et al., 2011). Fig. 5 illustrates the TEM images of pristine and three-surface modified MWCNTs. The figure demonstrates that an isolated MWCNT consists of a concentrically nested array of single-walled CNTs following an outer diameter in the range of 5–25 nm and the hollow interior tube diameter of approximately 2 nm. The purification and oxidation treatment on the surface of the modified MWCNTs considerably enhanced their specific surface areas compared to the pristine-MWCNTs, while the surface modification have reduced the volume of micropores and the mean diameter of the pores. This can be attributed to the removal of impurities from MWCNTs and the increment of functional

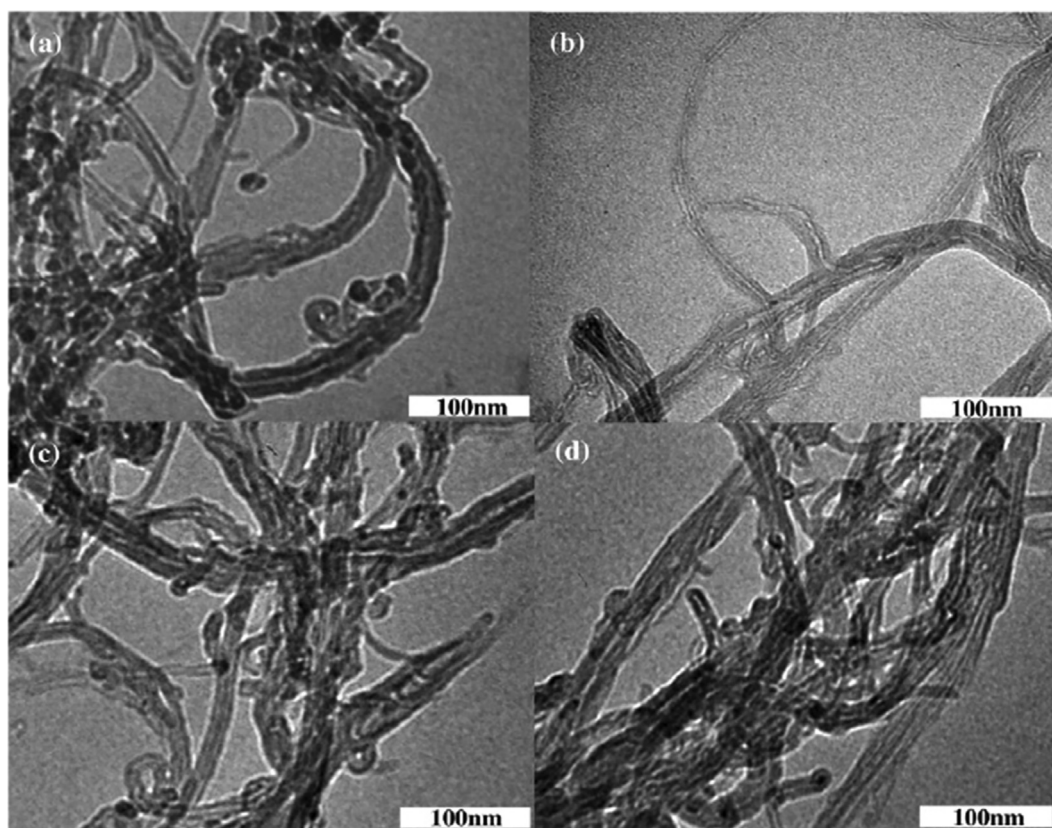


Fig. 5 TEM illustrations of (a) pristine-MWCNTs, (b) purified-MWCNTs (c) H_2SO_4 -MWCNTs and (d) $\text{Na}_2\text{S}_2\text{O}_8$ -MWCNTs. Reprinted from (Pu et al., 2013) with permission from Elsevier.



Fig. 6 Representation of ZnO nanoparticles for thallium removal. Reprinted from (Azonano).

groups on the surface of MWCNTs (Babanezhad et al., 2020; Dahal et al., 1998; Chen et al., 2017).

It is worth noting that the adsorption of Tl (I) on MWCNTs profoundly relies on pH and ionic strength. Those MWCNTs that possess more hydrophilic groups and negative surface charges may adsorb the highest amount of Tl(I).

5.4. Manganese dioxide (MnO_2) nanoparticles

MnO_2 is a promising adsorbing agent to remove heavy metals (Pan et al., 2014). In recent years, nano-sized MnO_2 has attracted attention compared to conventional forms because

it has various advantages such as a large surface area, a large porous structure, and strong interaction between pollutants and adsorbents. Therefore, the use of nano-sized MnO_2 can significantly improve absorption performance compared to conventional forms. For instance, the maximum absorption capacity of nano-sized MnO_2 for thallium removal is $672 \text{ mg Tl (I) g}^{-1}$, which is much bigger than the highest absorption capacity of conventional MnO_2 ($203 \text{ mg Tl (I) g}^{-1}$) (Wang et al., 2018; DASHTI, K.H., H. Aghaie, and M. Shishehbore, Adsorption of thallium (III) ion from aqueous solution using modified ZnO nanopowder., 2011). Amorphous hydrous manganese dioxide (AHMO) and polymer-based nano-sized MnO_2 are regarded as two novel sorts of modified MnO_2 , which have been currently under investigation by Wan et al (Tian et al., 2017). They perceived that despite the lower adsorption capacity of AHMO compared to nano-sized MnO_2 , AHMO can be an appropriate alternative to decrease the amount of thallium in potable water to meet the water standards regulated by China (Tian et al., 2017; Dhiman and Kondal, 2021).

5.5. Zinc oxide (ZnO) nanoparticles

Adsorption is considered as an efficient procedure among various techniques to remove heavy/toxic contaminant (such as thallium) owing to its noteworthy features including low cost, simplicity of availability and low operation time. After modification with sodium phosphate solution (SPS), ZnO nanopowder has great potential as an adsorbent for removing Tl (I)

ions from aqueous solutions (National Primary Drinking Water Regulations: Thallium (Technical Version), 1995; Deng et al., 2016; CCME, 2002; China, GB3838-2002, 2002.). Dashti et al. experimentally investigated the effect of adding sodium phosphate solution on improving the efficiency of ZnO nanopowder in removing thallium. They resulted that 5% w/v of SPS eventuated superior adsorption efficiency. Experimental data has shown that the adsorption efficiency rely on some momentous operational/functional factors including initial solution's pH, contact time, amount of employed adsorbent, temperature and the thallium concentration at the beginning of the process. They also perceived that under the optimum situations (solution pH = 6; contact time = 1 hr; adsorbent amount = 0.1 g; thallium concentration = 50 mg. L⁻¹ and temperature = 25 °C), the highest adsorption percentage of Tl (I) ion applying modified ZnO nanopowder was achieved 92.8% (xxxx). Compared to different types of nano-based adsorbents, modified ZnO nanopowder shows better performance due to its abundance, affordability and high adsorption capability (Wu, 2019). Fig. 6 presents an illustration of ZnO nanoparticles.

5.6. Nano-magnetite-based biochar

In recent years, much attention has been paid to the development of promising/regenerated nano-based materials in conjunction with advanced oxidation to remove thallium (Tl) from a variety of surface/groundwater resources. Nano-magnetite-based biochar (Fe₃O₄/C) is known as a new type of nano-adsorbent due to its luminous properties such as high porous structure and abundant active binding sites (Babanezhad et al., 2021). Li et al. experimentally investigated the efficiency of Fe₃O₄/C for the removal of Tl (I) from wastewater sources. They corroborated that the capacity of Tl(I) adsorption from wastewater applying Fe₃O₄/C nano-adsorbent is significantly increased at 1123 mg.g⁻¹ (Li, 2020).

6. Conclusions and future outlook

This review article aims to provide both expert and non-expert readers with a comprehensive and systematic overview of the latest promising nano-based materials for the removal of thallium as one of the most toxic chemical elements present in water/wastewater sources. Despite the existence of promising and efficacious techniques to control and manage thallium-containing wastewater, these technologies are still at the infancy stage in comparison with other metal contaminants. With the increasing amount of thallium in the world, cost-intensiveness of conventional methods (i.e., precipitation, ion exchange and solvent extraction) and its high toxicity to various microorganisms and human-health, the development of affordable technologies to mitigate its distribution in various aqueous/ non-aqueous sources are of great importance. Adsorption technology applying nano-based materials have recently become a viable option to overcome the operational/-functional drawbacks of traditional techniques that are emerging as an economical, reliable and eco-friendly method to control the distribution of thallium in water/wastewater sources. These novel techniques need to be further developed to prepare theoretical foundations for industrial-based utilizations at the commercial level.

Declaration of Competing Interest

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

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