

<sup>1</sup> Abdolmajid FADAEI

## COMPARISON OF URANIUM REMOVAL FROM GROUND AND SURFACE WATERS THROUGH DIFFERENT TECHNIQUES: A REVIEW STUDY

<sup>1</sup> Department of Environmental Health Engineering, School of Health, Shahrekord University of Medical Sciences, Shahrekord, IRAN

**Abstract:** Uranium (U) is a trace radioactive element distributed within the surface and ground waters through various sources, including natural and human-made activities. This study aimed to present a holistic review of uranium removal from groundwater. According to findings present study, in ground waters the highest concentration of uranium 27 to 10,100 µg/L was found in USA, and the lowest concentration was 3 to 8.6 µg/L found in India, while in surface waters the highest level of uranium 0.05 to 900 µg/L was found in Turkey, and the lowest concentration was 0.13 to 590 ng/L found in Japan, and the WHO and EPA guideline value of 30 µg/L. Various treatment techniques used for uranium removal, including adsorption, conventional coagulation, chemical precipitation, bioremediation, nanofiltration and reverse osmosis, and ion exchange, have been considered widely and established to propose acceptable findings. These methods can be used in future research to remove uranium (U (IV) and U(VI)) from polluted waters in both experimental and real-world.

**Keywords:** groundwater, radioactive, surface water, uranium removal

### 1. INTRODUCTION

Groundwater often includes mineral pollutants like fluoride, uranium, arsenic, and boron (Shen & Schäfer 2014). Longer-term exposure to these pollutants can cause health impacts in humans. For instance, ingestion of excess fluoride results in dental and skeletal fluorosis (Fawell *et al.* 2006; Fadaei & Amiri 2013), and permanent intake of uranium through potable water has toxic impacts on kidneys. Uranium is present in the Earth's layer with a mean redundancy of 2.7 mg/kg, whilst granite and phosphorite rocks may contain elevated levels of up to 15 mg/kg and 120 mg/kg, respectively (Bowman 1997). Uranium is released into the environment during medical and industrial activities and nuclear energy events, including nuclear power plants, nuclear weapons experiments, ore mining, and manufacturing, which may pollute aquatic sources, particularly groundwater (Cooper *et al.* 2021). Uranium contamination in groundwater is an issue of anxiety to various nations worldwide, e.g., India, Japan, USA, Norway, Canada, and Finland (Katsoyiannis & Zouboulis 2013; Atkins *et al.* 2016). Among the most frequent types of uranium in water sources are the anionic carbonate mixtures, such as  $\text{UO}_2(\text{CO}_3)_2^{-2}$  at pH levels less than 7 and the  $\text{UO}_2(\text{CO}_3)_4^{-3}$  at pH levels above 8. When pH levels are between 5 and 6.5, the neutral  $\text{UO}_2\text{CO}_3$  may also form a vital sector, which varies from 20% to 90% depending on the pH level (Tolkou *et al.* 2020). The effluent levels of uranium may reach 10 mg/L, which is above the present limit on uranium in the tolerable daily intake (Frisbie *et al.* 2013). The United States Environmental Protection Agency (EPA) has defined the maximum pollutant levels of 2 and 30 µg/L for thallium and uranium in potable water, respectively (Huang *et al.* 2021). The nature uranium concentration of seawater is around 3–9 mg/L (Hu *et al.* 2018).

Environmental outcomes and health risks associated with uranium mills are shown by two main methods. One is surface soil/water pollution by abrasion and wind diffusion of radioactive matter and the other is air pollution by Rn release (Abdelouas *et al.* 2018).

Natural uranium has both chemotoxicity and radiotoxicity. Water intake-based dose calculation revealed no significant radiological toxicity after exposure to natural uranium up to 1200 µg/L in groundwater (Hakonson-Hayes *et al.* 2002). Conversely, the uranium chemical toxicity causes a greater health problem as compared with its radiological toxicity. According to research studies, uranium is mainly stored in kidneys and bones, and long-time ingestion of uranium may raise the risk of renal deficiencies (Hakonson-Hayes *et al.* 2002). Expanding technologies and techniques for effective removal of uranium in a cost-effective manner seems to be essential.

Many studies have been conducted on uranium removal methods, such as ion exchange, membrane based separation, reverse osmosis, nanofiltration, ultrafiltration, chemical precipitation, biological adsorption, adsorption, bioremediation, electrochemistry, photocatalytic process, and solvent extraction (Kuncham *et al.* 2017; Tripathi *et al.* 2018; Ataei *et al.* 2020; Fadaei 2022). Some research studies have mentioned the advantages and limitations of uranium purification (Kuncham *et al.* 2017;

Tripathi *et al.* 2018; Ataei *et al.* 2020). Each technique has its own advantages, disadvantages, and effective factors and works in an efficient way under best conditions. Therefore, choosing a proper effective technique to eliminate uranium from water sources is essential. This study aimed to present a holistic review of various methods of uranium removal from groundwater.

## 2. METHODS

This review has principally focused on methods and processes. Several papers on the topic were retrieved from databases, such as Google Scholar, Web of Science, and Science Direct. Keywords, such as “surface water”, “drinking water”, “ground water”, “water treatment” “uranium removal”, and “adsorption” were used to retrieve proper papers. After a thorough search and removing articles that were not directly related to uranium removal from water, a total of 125 original papers were identified eligible to be included within the review. The review articles providing a perception of various mechanisms of each treatment were excluded. Types of water, such as surface water, sea water, and groundwater, were investigated in this study.

## 3. RESULTS AND DISCUSSION

These articles used various methods, including adsorption (biosorbents, electrosorption nanoparticles (NPs)) (13), bioremediation and biological method (8), nano-filtration (2), nano-filtration and reverse osmosis (2), ultrafiltration (2) reverse osmosis (1), photocatalytic process (7) ion-exchange (2), coagulation (1), and electrocoagulation(1) ( Tables 1,2,3,4,5,6).

### ■ Adsorption

Adsorption is one of the most effective strategies to eliminate several toxic contaminants from aqueous environments due to its easy design, facilities, low price, high adsorption yield and wide compatibility(Ahmadi *et al.* 2020).Lemons et al. reported a rate of about 80% for polonium and 90% for plutonium removal from drinking water using co-precipitation(Lemons *et al.* 2018). The results from this study showed that the highest removal performance of uranium was1549.32 mg/g for thiol-functional hydrotalcite, and the lowest removal performance was32.46 mg/g for carbon nanotubes (Figure 1 and Table 1).

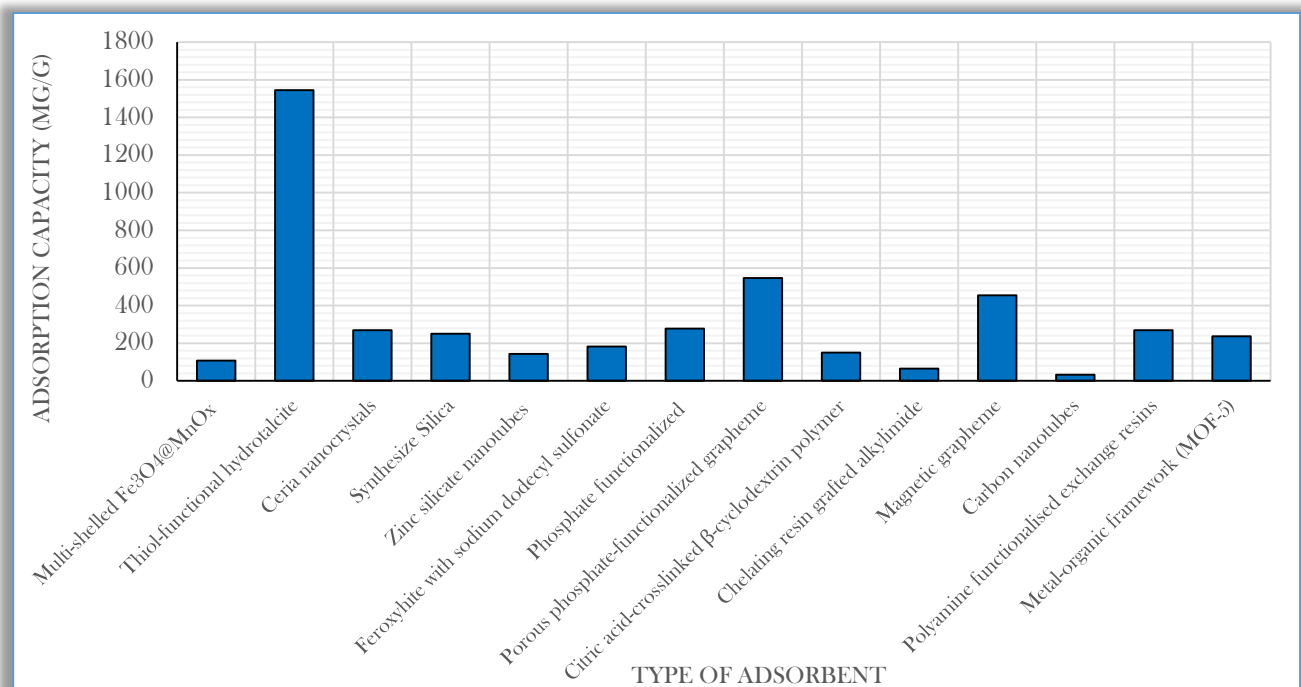


Figure 1. Removal performance of uranium by different adsorbents

One study reported the optimal adsorption capacity for uranium(VI) to be 127.23 mg/g at pH 7.0 following a 6h exposure(Wang *et al.* 2016). Another study found Al<sub>2</sub>O<sub>3</sub> aerogels to be potential adsorbents for uranium removal (Ding *et al.* 2021). Mishra et al. reported the utmost sorption of around 95% to occur at the pH span of 5 to 6 through the biochar process(Mishra *et al.* 2017). In a study, Yekta et al. reported the best capacity adsorption of 23.5849 mg of VI(U)/g of NiO/NPs/Ag-clinoptilolite(Yekta

*et al.* 2016). Another study found the efficiency of uranium removal using adsorption media, such as iron oxides and titanium oxide to be more than 90% (Katsoyiannis & Zouboulis 2013).

Table. 1 Adsorption method for uranium elimination from various types of water

Technique	Environment	Elimination performance	Comment	Ref
Multi-shelled Fe <sub>3</sub> O <sub>4</sub> @MnO <sub>x</sub> hollow microspheres	Groundwater	106.72 mg/g (90%)	pseudo-second-order model, reaction time 60 min, pH=2–11, 298 K	(Song <i>et al.</i> 2019)
Adsorption (Thiol-functional hydroxalcite)	Aqueous solutions	1545.32 mg/g (99.06%)	(VI) 30 mg/L, time 150 min, pH= 3.0, temperature 30 °C	(Xu <i>et al.</i> 2019)
Adsorption (Ceria nanocrystals)	Aqueous medium	Adsorption capacity of 270 mg/g	U(VI) 0.5–70 mg/L, pH=6, contact time 20 h, Langmuir and Freundlich adsorption model	(Kunham <i>et al.</i> 2017)
Adsorption (Synthesize Silica Zn <sub>2</sub> SiO <sub>4</sub> and Zinc silicate nanotubes ZnSNTs)	Aqueous solutions	Adsorption value 250 mg/g and 143 mg/g	SNTs 53.8 m <sup>2</sup> /g, ZnSNTs 8.8 m <sup>2</sup> /g, pH 6, U(VI) 10mg/L, time 60 min, Langmuir model	(Tripathi <i>et al.</i> 2018)
Adsorption (Feroxyhite (δ-FeOOH) dispersed with sodium dodecyl sulfonate (SDS))	Aqueous solutions	Adsorption capacity of SDS/δ-FeOOH for TI <sup>+</sup> and UO <sub>2</sub> <sup>2+</sup> was 182.9(99.5%) and 359.6(99.7%) mg/g	UO <sub>2</sub> <sup>2+</sup> 10 mg/L, pH 7, Time 10 min, Freundlich isotherm	(Huang <i>et al.</i> 2021)
Adsorption (Phosphate functionalized poly(vinylalcohol)/poly(acrylic acid))	Aqueous solutions	Adsorption capacity 277.78 mg/g	Uranium 30 mg/L, pH 5.5, temperature 318 K, time 180 min	(Xie <i>et al.</i> 2020)
Electrosorption (Porous phosphate-functionalized graphene)	Aqueous solutions	Adsorption value equal to 545.7 mg/g	pH 5.0, 1.2 V, U(VI) 100 mg/L, 298 K, 21 min	(Liao <i>et al.</i> 2019)
Adsorption (Citric acid-crosslinked β-cyclodextrin polymer)	Aqueous solutions	Adsorption capacity 150 mg/g	U(VI) 5–80 mg/L, pH=4.0, reaction time 60 min and T=25 °C, y Langmuir and Freundlich isotherm	(Ullah <i>et al.</i> 2019)
Adsorption (Chelating resin grafted alkylamide)	Aqueous solutions	Adsorption value 64.9 mg/g	U(VI) 100 mg/L, pH 5.0, reaction time 48 h, Freundlich isotherm	(Liu <i>et al.</i> 2018b)
Nanocomposite (Magnetic graphene)	Aqueous solutions	455 mg/g (90.5%)	U (VI) 50–250 mg/L, pH 6, adsorbent dosage 300 mg/L, 60 min at room temperature, Langmuir model	(El-Maghrabi <i>et al.</i> 2017)
Adsorption (Carbon nanotubes)	Aqueous solutions	32.46 mg/g (95%)	U 20 mg/L, pH 5.0, Time 10 min, Langmuir model	(Yu & Wang 2016)
Adsorption (Polyamine functionalised exchange resins)	Aqueous solutions	Adsorption capacity 269.50 mg/g	U 1000 mg/L, pH 1–6, time 24 h, at room temperature, Langmuir model	(Amphlett <i>et al.</i> 2018)
Adsorption metal-organic framework (MOF-5)	Aqueous solutions	Adsorption capacity 237.0 mg/g	U(VI) 0.01 M, pH 5.0, T= 298K, 5 min	(Wu <i>et al.</i> 2018)

Nano-adsorbents are used for removal of uranium and other compounds from aqueous solutions due to their high surface area, porous frame and short adsorption equivalency time. Various types of nano-adsorbents, such as modified silica, metal oxides, nonporous carbon/polymer composite, graphene oxide, graphene oxide/activated carbon felt, layered double hydroxide/graphene hybrid metal, activated carbon, multiwalled carbon nanotubes (MWCNTs), graphene oxide and iron oxide/graphene nanocomposite have been used for uranium removal from water and wastewater. In general, nanocomposites have the highest adsorption capacities as compared with pure constituents (El-Maghrabi *et al.* 2017). One study illustrated that the adsorbent (Titanium dioxide) was capable of reducing uranium by about 99% (Wazne *et al.* 2006).

Another study reported the adsorption capacity of Titanate nanotubes (TNTs) for U(VI) to be 333 mg/g at pH span from 4 to 6 (Liu *et al.* 2016).

A study also found the removal of uranium to be 81, 59, 40 and 70 mg/L using electrospun nanofibers, TiO<sub>2</sub> NPs, SrTiO<sub>3</sub> NPs and TiO<sub>2</sub> electrospun nanofibers, respectively (Hu *et al.* 2018). Another study reported that the adsorption capacity was obtained to be 595.3 mg/g using hydroxylated titanium carbide (Ti<sub>3</sub>C<sub>2</sub>(OH)<sub>2</sub>) for U(VI) (Zhang *et al.* 2016).

Another study stated that the best adsorption capacities of plasma- and chemical-grafted amidoxime/carbon nanofiber hybrids (p-AO/CNFs and c-AO/CNFs) used for removal of <sup>238</sup>U(VI) from wastewater, seawater, and groundwater were 588.24 mg/g and 263.18, respectively (Sun *et al.* 2017). In a study, the capability of uranium adsorbent was reported to be between 0.1 and 3.2 mg/g in the temperature range of 15–30 °C for an examination phase ranging from 2 hours to 240 days using synthetic polymers with amidoxime ligands for uranium removal from seawater, (Kim *et al.* 2013). One study found the adsorption capacities of 0.66 and 0.74 mol/kg at pH=1 to 5 by using polyacrylamide-expanded perlite (Akkaya 2013). Additionally, using polyacrylonitrile fibers in a research study, the utmost adsorption capacity was reported to be 163 mg/g for U(VI) (Wang *et al.* 2020a). Fan *et al.* demonstrated that magnetic Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub> composite particles were highly capable of removing uranium

from aqueous media and the utmost U(VI) adsorption capacity was around 52 mg/L at 25°C (Fan *et al.* 2012). In another study, the adsorption capacity of carbonaceous adsorbent (THC-COOH) to remove uranium from polluted water was obtained to be 205.8 mg/g at pH 6 (Liu *et al.* 2013).

In a study, the maximum capacities of about 22.2 mg/g and 25.64 mg/g were obtained for Graphene oxide (GO) and Fe-Ni/GO, respectively (Rohith *et al.* 2020). Using a metal-organic framework for U(VI) and Th (IV) in another study, the adsorption capacity was obtained to be 227.3 and 285.7 mg/g, respectively (Alqadami *et al.* 2017). Yang *et al.* found the adsorption capacity of up to 200 mg/g U(VI) using metal-organic framework (Azo and Amide Groups) (Yang *et al.* 2018).

Using MOF@cotton fiber (HCF) composite in another study by Yang and *et al.*, the best sorption capability for U(VI) was obtained to be 241.28 mg/g at pH 3 (Yang *et al.* 2020). These methods (various adsorption processes) need to be applied in natural waters (surface and ground waters) as most of the presented results were obtained using syntactic waters.

### ■ Bioremediation process

It was assumed that uranium would be sedimented from the watery stage, but would not be eliminated from the place. This attitude would be valuable because no second product and no next byproducts are generated. It was mainly supposed that such a technique would contain a regularity of boreholes arranged in a method that provided optimum underground remediation using native bacteria. Today, bioremediation of groundwater affected by dissolved metals, metalloids, and radionuclides may be one of the most important problems for in situ environmental remediation (Table 2). Uranium removal from the ground requires long-time stability of the sediment, indicating that a redox buffer is perhaps produced and uranium decreased to prepare adequate stability of uraninite to considerably retain the uranium level below the standard limits in the groundwater after remediation (Abdelouas *et al.* 2018). In their study, Saini *et al.* reported an utmost adsorption capability of 588.24 mg/g in 2 h using biosorption technology (melanin pigment) (Saini & Melo 2013). One study reported that *Catenella repens*, a red weed grown in the sea, is capable of finely absorbing uranium (VI) from aqueous media (Bhat *et al.* 2008). Another study reported that the biosorption of thorium by *Rhizopus arrhizus* revealed prosperous removal of about 90–95% of thorium (White & Gadd 1990). In a study by Xie *et al.* an improvement was observed in the uranium (VI) removal with raising pH level at 5 h, for example from 19.4% at pH 4.52 to 99.7% at pH 8.30 (Xie *et al.* 2018). One study reported that the precipitation of uranium increased from ≤55% up to 70–90% within the pH range of 2–8 in presence of *Pseudomonas putida* bacteria (Kenney *et al.* 2018). A study by Abdehvand *et al.* indicated that the utmost uranium elimination was 97% at pH 6.4 using *Shewanella sp* RCRI7 bacteria (Abdehvand *et al.* 2017).

Table. 2 Bioremediation and biological treatment for elimination of uranium from various types of water

Technique	Environment	Elimination performance	Comment	Ref
Biological ( <i>Pseudomonas putida</i> )	Aqueous solutions	Precipitation rate of 70–90%	U 10 mg/L, pH 2 to 12,	(Kenney <i>et al.</i> 2018)
Bioremediation (in situ)	Groundwater	99.9% after 90 days	U(VI) 235 mg/L, pH 7.4, at 24°C	(Abdelouas <i>et al.</i> 2018)
Bioreduction	seawater	19.4% at pH 4.52 and 99.7% at pH 8.30	Contact time 5 h, 0.001 mol/L	(Xie <i>et al.</i> 2018)
Biological ( <i>Arthrobacter</i> G975 strain)	Groundwater	85% at pH 7.3 at 24–h	U(VI) (61.76 µM/l), temperature = 25 °C	(Carvajal <i>et al.</i> 2012)
Biological ( <i>Shewanella oneidensis</i> )	Water	87.5%	pH = 8.5, U (VI) (1 mmol/l)	(Alessi <i>et al.</i> 2014)
Biological ( <i>Saccharomyces cerevisiae</i> )	Water	98% after 1000–min	pH = 5.0, U (VI) (10 mg/l), temperature = 30°C, 250 rpm	(Zheng <i>et al.</i> 2018)
Biological ( <i>Yarrowia lipolytica</i> )	Aqueous solutions	35% after 15–30 min and 45.5% after 24 h	U (VI) 50 µM, pH= 7.5 at 30 °C	(Kolhe <i>et al.</i> 2020)
Bioremediation ( <i>Rhodospiridium toruloides</i> )	flooding water	350 mg/g after 48 h	U 6 mM, 30 °C and 130 rpm	(Gerber <i>et al.</i> 2018)

### ■ Phytoremediation

This technique can be used for in-situ or ex-situ removal of pollutants from ground and surface waters. Phytoremediation mechanisms of this technique include rhizofiltration, hydraulic control, and phytovolatilization (Dinis & Fiúza 2021).

Rhizofiltration is the absorption of pollutants by the roots of plants that are grown hydroponically. The pollutants are then translocated, and aggregated into different parts of the plant, such as plant shoots and leaves. In hydraulic control, the motion of pollutants is slowed down in groundwater using deep-rooted plants. Phytovolatilization is presented to treat water with water and releases the pollutants into the air via their leaves (Dinis & Fiúza 2021). Another study by Yang et al. demonstrated that the bean (*Phaseolus vulgaris* L. var. *vulgaris*) reduced the level of uranium up to 90.2% at 12 h and up to 98.9% at 72 h (Yang et al. 2015).

A study by Vera Tome et al. showed that by rhizofiltration using *Helianthus annuus* L. the natural uranium  $^{226}\text{Ra}$  were fixed in the roots by about 50% of and 70%, respectively (Tomé et al. 2008). One study indicated that the root surfaces of ordinary reed in a wetland could absorb uranium by about 87.1% (Wang et al. 2015b). Another study reported the highest rate of uranium accumulation in Rhizofiltration (*Raphanus sativus* L), with a mean bioconcentration factor (BCF) of 2683.5 (Han et al. 2021). In a study by Tayyab Ahsan et al., bacterial consortia (*Leptochloa fusca* (L.)) was found to further improve uranium sorption capacity up to 53–88% (Ahsan et al. 2017).

### ■ Photocatalytic process

Undoubtedly, investigation of the mechanism of uranium (VI) conversion during photocatalytic reactions is very important for the expansion of suitable photocatalysts and enhancing the reduction performance of uranium (VI). Nevertheless, in most of current research, further attention seems to be paid to the reasons for improvement of photocatalysts efficiency rather than the process of uranium (VI) conversion. Despite the photocatalysts efficiency, uranium (VI) reduction was done by photogenerated electrons on the CB of irradiated catalysts or reductive radical intermediates generated while electron sacrifices exist (Yu et al. 2019). Investigation of the effect of environmental parameters, such as pH, concentration of ions, catalyst dose, uranium (VI) level, coexisting ions, dissolved oxygen (DO), organic matters (OMs), initial level of metals, intensity of light, photocatalyst value, temperature, etc., on the photocatalytic activity is necessary (Table 3). A study by Wang et al. demonstrated that photoreduction reduced the uranium level up to 95% at 135 min, initial uranium (VI) concentration of 0.42 mM, and pH 5.5 (Wang et al. 2015a). One study reported that the best elimination rate of 99% was obtained with 0.021 mM uranium (VI) in 240 min and UV–visible light (300 W Xe arc lamp) (Guo et al. 2016). Another study by Li et al. demonstrated that the photoreduction reduced uranium level up to 80% at 240 min, with an initial uranium (VI) concentration of 0.42 mM, pH 3 and 150 W Xenon arc lamp (Kim et al. 2015). The other study reported the photocatalytic efficiency to be 80% within 180 min, with an initial uranium (VI) concentration of 0.21 mM at pH 4 using photocatalytic (UV–visible light and  $\text{Ti}_3\text{C}_2/\text{SrTiO}_3$ ) (Deng et al. 2019). In a study by Liu et al., the photocatalytic efficiency was obtained to be 90% within 240 min, initial uranium (VI) concentration of 0.084 mM at pH 5 using photocatalytic (Simulated solar light and Niobate/Titanate) (Liu et al. 2018a).

Table. 3 Photocatalytic process for elimination of uranium from various waters

Technique	Environment	Elimination performance	Comment	Ref
Photocatalysis/ Photoconversion	Seawater	100% at 170min (19.49 mg/g) and pH = 6.0	TiO <sub>2</sub> =0.6 g/l, 300 W high–pressure Hg lamp, U(VI) (0.0001 mol/ L)	(Matteoda et al. 2019)
Photo–reduction	Water	59% at 4–h	U(VI) (20 mg/l), TiO <sub>2</sub> , pH = 6.9, photo intensity = 160 mW/cm <sup>2</sup>	(Jiang et al. 2018)
Heterogeneous photocatalytic reduction	Water	94% at 120–min	U(VI)=0.25 mmol/L, pH = 3.0, 125W lamp, g–C <sub>3</sub> N <sub>4</sub> /TiO <sub>2</sub> = 0.25 g/L, TiO <sub>2</sub> = 1 g/L	(Salomone et al. 2015)
photocatalytic reduction	Water	84.5% (~2990 )mg/g at 60 min	300 W Xe lamp, pH = 6.0, C(UO <sub>2</sub> <sup>2+</sup> ) = 0.01 mol/L	(Wang et al. 2020b)
photocatalytic reduction	Waste water	96.02% ( 2880.6 mg/g)	LED light, mGO/g–C <sub>3</sub> N <sub>4</sub> =1 – 5 mg, pH 6, c <sub>0</sub> =1–100 mg/L, T= 298 K	(Dai et al. 2020)
photocatalytic reduction	Seawater	more than 99%(500 mg/g) after 30 min with visible light and higher than 98% in 60 min with sunlight	350 W Xe lamp, pH 4–6, c <sub>0</sub> =100 mg/L	(Gong et al. 2021)
Photoconversion	Seawater	About 100% in 100 min	U(VI) 0.2 mM, TiO <sub>2</sub> = 0.6 g/L, UV light (350 W mercury discharge lamp)	(Godoy et al. 2019),

## Membrane processes

Nanofiltration membranes are capable of selectively removing uranium (VI) from mineral water with a comparatively high selectivity, regardless of a high level of alkaline and alkaline–earth cations. As a result, nanofiltration tools can be weighed appropriate for decreasing the uranium (VI) level in potable water to a level below the maximum acceptable level determined by the World Health Organization (WHO). The rejection of uranyl is largely due to the effect of charge between the uranyl carbonate complex and the charged membrane (Favre–Réguillon *et al.* 2008).

Despite the strengths of membrane techniques (reverse osmosis and nanofiltration), fouling, scaling, high energy and capital costs, and adjustment of pH of the exit water are among their limitations (Khedr 2009). Natural organic matter (NOM) and co–existing ions significantly affect uranium maintenance in nanofiltration/reverse osmosis in natural waters. Besides calcium, NOM can shape several soluble complexes with uranium. The uranium–NOM complex causes an increase in the amount of uranium precipitated to the ultrafiltration membrane. However, the complexes cannot be retained as they are still smaller than the size of ultrafiltration membrane's pores. Given the effective NOM removal by nanofiltration/reverse osmosis, the efficient rejection of any uranium bound to NOM is expected. Calcium can also affect uranium owing to the formation of stable complexes of calcium–uranyl–carbonate (Shen & Schäfer 2014). In comparison to ion exchange methods, the main benefit of membrane filtration is that it is a continuous process with no need for further chemical products (e.g., adsorbent regeneration). This method can be used as a viable and cost–effective technique for in situ water remediation (Table 4).

The study of Hoyer *et al.* demonstrated that 99% uranium removal was achieved using nanofiltration and reverse osmosis membranes (Hoyer *et al.* 2014). One study found that the nanofiltration efficiently rejected 95–98% of uranyl–carbonate complexes (Favre–Réguillon *et al.* 2008). Reverse osmosis has been used for removal of radium<sup>-226</sup>, cesium<sup>-137</sup>, strontium<sup>-89</sup>, iodine–131, radium<sup>-228</sup>, and uranium (Sorg 1988; Dinis & Fiúza 2021).

Favre–Réguillon *et al.* could achieve an uranium removal of 90% using nanofiltration (Favre–Réguillon *et al.* 2008). Radium, uranium, and radon were removed using nanofiltration and reverse osmosis (Khedr 2013).

In a study, reverse osmosis membranes were used for the purification of uranyl sulfate compounds with uranium levels of above 5000 mg/L and retention in the range of 91% to 99.8% were achieved (Sastri & Ashbrook 1976). In another study, Khedr demonstrated that reverse osmosis and nanofiltration are in defined shapes preferable to the most popular traditional techniques of resin, chemical sedimentation, coagulation, and adsorption on surface active medium. Whilst reverse osmosis and nanofiltration could effectively retain uranium and radium, they were incapable of eliminating gaseous contaminants like radon (Khedr 2013). One study showed that reverse osmosis and nanofiltration can eliminate uranium by about 99% (Katsoyiannis & Zouboulis 2013).

Table. 4 Membrane filtration for elimination of uranium from various waters

Technique	Environment	elimination performance	Comment	Ref
Nanofiltration	Drinking water	96%	U 0.02 mg/L, pH 7, pressure of 1 bar, temperature 20 °C	(Favre–Réguillon <i>et al.</i> 2008)
Nanofiltration	Mine Water	rejections more than 95%	feed flow rate 200–225 L/h, flux 30 to 35 L/m <sup>2</sup> ·h operating pressures 5 to 20 bar, T= 25 °C pH 3	(Mullett <i>et al.</i> 2014)
Reverse osmosis and nanofiltration	Groundwater	99%	feed pressures of 6 and 8 bar for NF and RO, pH=7.5–8, 25 °C	(Khedr 2013)
NF/RO	Drinking water	Up to 95%	High performance and Membrane fouling	(Shen & Schäfer 2014)
UF	Waters	retention coefficient 0.88–0.91	flow rate=82–86 L/(m <sup>2</sup> ·h), U(VI) 10 mg/L, pH 7–8	(Yurlova 2020)
UF	water	retention coefficient of 0.94–0.95	U(VI) 10 mg/L, pH=5–9, operating pressure 0.2 MPa,	(Kryvoruchko <i>et al.</i> 2004)

## Other techniques for uranium removal from various types of water

### — Ion exchange

This operation unit capability and the resin selectivity are significant factors affecting resin selection. Cation and anion resins have been evaluated and used for uranium elimination. There are significant

remarks when evaluating the practicality of the ion exchange technique for uranium elimination. Water quality factors like inflow uranium level, water pH, competing ions, such as sulfates, must be advised during the assessment of the system's efficiency (Table 5) (Dinis & Fiúza 2021). One study used resin (anion exchanger resin) to remove uranium from water and obtained a removal performance of 97 to 99% (Campbell *et al.* 2018). Another study reported that anion exchange is an extensively used technique, providing uranium elimination of above 95% (Katsoyiannis & Zouboulis 2013). A study indicated that the best elimination (92–93%) was obtained with 20–25 mg/L of ferric sulfate at pH 10 (Sorg 1988). In their study, Barton *et al.* indicated that ion-exchange is the best proficient elimination technique because it can remove about 98% of anionic uranium carbonate types (Barton *et al.* 2004). Another study reported that up to 2,500 µg/mL of uranium was kept with up to 99% efficiency at pH 3 (Aziz *et al.* 2010). In a study by Petersková *et al.*, the maximal sorption capacity was reported to be 22.78 mg/g for uranium(VI) using resin with phosphonic and sulphonic acidic groups (Petersková *et al.* 2012).

#### — Conventional coagulation

Uranium removal using the coagulation method is possibly done via adsorption and co-precipitation of the dissolved uranyl complexes by the coagulant precipitates. In this method, water pH, the level of radionuclides, and the coagulant dose significantly affect elimination performance (Baeza *et al.* 2006). Materials, such as lime, alum, barium chloride, ferrous sulfate, sodium hydroxide, ferric sulfate, and ferric chloride are used for uranium removal in this method. Though being efficient, common methods of uranium removal have disadvantages like sludge production, high cost, and challenge of final disposal (Dinis & Fiúza 2021).

There are various instances explaining the use of this technique to remove uranium. For example, one study indicated that barium chloride is particularly used for radium removal from uranium mill process waters, and the removal rates were reported to be about 95–99% (Vance *et al.* 2006). The removal value for the same content of 25 mg/L of aluminum sulfate was reported to be only 48% and 21%, respectively, at pHs 8 and 4 (Sorg 1988). A study claimed that an efficiency of 80%, 92% and, 95% could be obtained respectively by the use of ferric sulfate, ferrous sulfate, and alum for uranium and cesium removal from water (Sorg 1988).

Katsoyiannis and Zouboulis stated that a removal efficiency of above 80% can be obtained at pH=6–10 by coagulation with ferric or aluminum salts, and lime is capable of removing uranium at rates above 90%, but only at pH more than 9.5 (Katsoyiannis & Zouboulis 2013). In their study, Nam Kim *et al.* used sodium hydroxide, calcium hydroxide, and ammonium hydroxide for uranium precipitation (Kim *et al.* 2011). Another study found the elimination of uranium(VI) by quartz sand in alkaline sodium chloride solutions to be about 75 to 96% at pHs 10.5 and 11.5 at 48 h (Kirby *et al.* 2020).

Table 5. Other techniques for uranium removal from various types of water

Technique	Environment	Elimination performance	Comment	Ref
Coagulation, settling, and filtration	Groundwater	Up to 95%	BaCl <sub>2</sub> and FeCl <sub>3</sub> , pH 10	(Khedr 2013)
Electrocoagulation	Mine water	99.7% at 120–min by 70 mA/cm <sup>2</sup> , 98% at 120–min by 40 mA/cm <sup>2</sup>	U (VI) 0.62 mg/L, pH = 2.68, Iron–stainless steel, Langmuir and Temkin isotherm	(Nariyan <i>et al.</i> 2018)
Anion–exchange resin	Groundwater	More than 90%	U 5 mg/L, pH 5, Time 1–8 h	(Phillips <i>et al.</i> 2008)
Weakly basic anion exchangers	Aqueous solutions	10 mg/g	U 10 µg/L, pH 6.5–9	(Riegel 2017)

#### World conditions of Uranium

According to findings of a study on ground waters, the highest uranium level of 27 to 10,100 µg/L was obtained in the USA, and the lowest level of 3 to 8.6 µg/L was found in India (Table 6), while in surface waters, the highest uranium level of 0.05 to 900 µg/L was found in Turkey, and the lowest uranium level of 0.13 to 590 ng/L was found in Japan (Table 7). WHO and EPA have recommended that uranium level in potable water should not exceed 30 µg/L (Table 8).

In a study, Åström *et al.* found uranium levels of above 200 µg/l in groundwater and above 80 µg/L in surface water in Boreal Europe (Sweden, Finland, Russia) (Åström *et al.* 2009). Another study showed that the uranium level in tap water of Al-Najaf, Iraq was below 1.9 µg/L (Abojassim & Mohammed 2017).

Research studies in Canada, Finland, and Norway reported populations that used potable water with uranium levels of 700 µg/L, 28 µg/L, and up to 20 µg/L, respectively. The highest levels were observed in ground water close to Helsinki with uranium concentration of 14870 µg/L (Hoyer 2017). Ground waters with high uranium levels in Kazakhstan, Australia and Canada are often found in uranium mining areas because these countries contribute to the world's uranium generation by 64% (Shen & Schäfer 2014).

Table 6. Uranium levels in ground water from several countries

Country	Region/province/city	Uranium level (µg /L)	Ref
China	Southern China	550–3360	(Ma <i>et al.</i> 2020)
Kosovo	–	0.012–166	(Berisha & Goessler 2013)
Kazakhstan	–	1.9–35.9	(Uralbekov <i>et al.</i> 2011)
Norway	South Norway	2.04–246	(Frenstad & Banks 2014)
Canadian	Canadian Aboriginal	1–1418	(Zamora <i>et al.</i> 2004)
USA	South Carolina	27–10,100	(Wagner <i>et al.</i> 2011)
USA	Washington	1.03–1180	(Kahle <i>et al.</i> 2018)
Iran	Urmia	Below 30	(Sohrabi & Amiri 2018)
Korea	Jurassic Granite Area	0.02 –1640	(Cho & Choo 2019)
India	Central Tamil Nadu	1.75–46.7	(Thivya <i>et al.</i> 2014)
India	Punjab	3–8.6	(Sharma <i>et al.</i> 2019)
Finland	Southern Finland	6–3400	(Prat <i>et al.</i> 2009)
Argentina	Córdoba	Up to 17.3	(Matteoda <i>et al.</i> 2019)
Brazil	Rio de Janeiro State	Up to 930	1. (Godoy <i>et al.</i> 2019)
Portugal	NE Portugal	8.2–3483	(Costa <i>et al.</i> 2017)
Switzerland	Alpine regions	0.05–92.02	(Stalder <i>et al.</i> 2012)
Saudi Arabia	Hail province	<0.8–90.8	(Duggal <i>et al.</i> 2021)
Bangladesh	Western Bangladesh	<0.2–10	(Duggal <i>et al.</i> 2021)

Table 7. Uranium levels in surface water from several countries4

Country	Region/province/city	Uranium level (µg /L)	Ref
USA	North–central Colorado	20 – 83	(Schumann <i>et al.</i> 2017)
Kazakhstan	Shu river	8–30	(Burkitbayev <i>et al.</i> 2012)
Japan	River	0.00013–0.590	(Somboon <i>et al.</i> 2019)
Australia	Richmond River	0.001–2.77	(Atkins <i>et al.</i> 2016)
Turkey	Izmir	0.05–900	(Akyil <i>et al.</i> 2009)
Argentina	Córdoba	Up to 0.47	(Matteoda <i>et al.</i> 2019)
Sweden	Northern Sweden	6–17	(Pontér <i>et al.</i> 2021)
Sweden	Streams (Kärsvik, Kårevik, Ekerum and Laxemar)	0.13–2.56	(Yu <i>et al.</i> 2019)
South Africa	Stream water	319	(Wang <i>et al.</i> 2012)
Finland	–	0.15–0.099	(Barescut <i>et al.</i> 2011)
Korea	–	0.01–49.7	(Yoon <i>et al.</i> 2013)
Germany	–	0.03– 48	(Gans 1985)
Norway	–	0.2–170	(Somboon <i>et al.</i> 2019)

Table 8 International uranium guidance levels (µg /L) for drinking water

Country/Organization	Level (µg /L)	Ref
World Health Organization	30	(Edition 2011)
United States Environmental Protection Agency	30	(USEPA 2018)
International Commission on Radiological Protection	1.9	(Protection 2007)
Canada	20	(Chen 2018)
Australia	17	(NHMRC 2011)
European Union	Not specified	(Directive 2013)
Japan	2	(Evans <i>et al.</i> 2019)
Malaysia	2	(Duggal <i>et al.</i> 2021)
Germany	10	(Duggal <i>et al.</i> 2021)
Uganda	5	(Duggal <i>et al.</i> 2021)
New Zealand	20	(Duggal <i>et al.</i> 2021)
South Africa	15	(Duggal <i>et al.</i> 2021)
Oman	15	(Duggal <i>et al.</i> 2021)

#### 4. CONCLUSIONS

The most common treatment techniques used for uranium elimination include ion exchange, bioremediation, reverse osmosis, nanofiltration, coagulation, and adsorption. The current findings have to be viewed in light of some limitations. Disadvantages of all processes were not available in most of the studies. The uranium removal by reverse osmosis and nanofiltration is very effective and the removal performance ranges from 90 to 99.8%. Disadvantages of these methods include scaling, fouling, high energy and fund expenditures, and the need for regulation of pH of the exit water. Removal performances obtained by coagulation with barium chloride, aluminum sulfate, ferrous sulfate, ferric sulfate, and aluminum sulfate range from 21 to 99%. Disadvantages of these processes include sludge generation, being costly, and the problem with final disposal. The elimination performance is based on the pH of raw water, kind of coagulant, coagulant content, and water compound. The most effective technique with a wide application is ion exchange whose elimination performance ranges from 95 to 99%. Adsorption is among other most effective methods for uranium removal from water and wastewater. Besides, elimination efficiency is reported to be more than 80%. The removal is mainly dependent on pH, initial level of pollutant, adsorbent content and kind, flow rate of water, reaction time, pollutant solubility and temperature. The uranium removal rate by biosorption ranges from 50 to 90%. The main advantages of biosorption include low price, high efficiency, low waste generation and



biosorbent regeneration, eco-friendly and possibility of contaminant recovery. Overall, research works on uranium elimination from different types of water have advanced significantly. These research studies are required to be commercially executable for uranium elimination from water. The highest uranium level of 27 to 10,100 µg/L was obtained in the USA, and the lowest level of 3 to 8.6 µg/L was found in India (Table 7), while in surface waters the highest uranium level of 0.05 to 900 µg/L was found in Turkey, and the lowest uranium level of 0.13 to 590 ng/L was found in Japan.

### Acknowledgements

The author thanks Shahrekord University of Medical Sciences. The author declares this research received no specific grant from any funding agency

### References

- [1] Abdehvand A. Z., Keshtkar A., Fatemi F., Tarhriz V. and Hejazi M. S. (2017). Removal of U (VI) from aqueous solutions using *Shewanella* sp. RCRI7, isolated from Qurugöl Lake in Iran. *Radiochimica Acta* 105(2), 109–20.
- [2] Abdelouas A., Lutze W. and Nuttall H. E. (2018). Uranium Contamination in the Subsurface: Characterization and Remediation. *Uranium*, 433–74.
- [3] Abojassim A. A. and Mohammed H. A.–U. (2017). Comparing of the uranium concentration in tap water samples at Al–Manathera and Al–Herra Regions of Al–Najaf, Iraq. *Karbala International Journal of Modern Science* 3(3), 111–8.
- [4] Ahmadi D., Khodabakhshi A., Hemati S. and Fadaei A. (2020). Removal of diazinon pesticide from aqueous solutions by chemical–thermal–activated watermelon rind. *International Journal of Environmental Health Engineering* 9(1), 18.
- [5] Ahsan M. T., Najam–ul–Haq M., Idrees M., Ullah I. and Afzal M. (2017). Bacterial endophytes enhance phytostabilization in soils contaminated with uranium and lead. *International journal of phytoremediation* 19(10), 937–46.
- [6] Akkaya R. (2013). Removal of radioactive elements from aqueous solutions by adsorption onto polyacrylamide–expanded perlite: equilibrium, kinetic, and thermodynamic study. *Desalination* 321, 3–8.
- [7] Akyil S., Aytas S., Turkoz D., Aslani M. A., Yusan S. D. and Eral M. (2009). Radioactivity levels in surface water of lakes around Izmir/Turkey. *Radiation Measurements* 44(4), 390–5.
- [8] Alessi D. S., Lezama–Pacheco J. S., Stubbs J. E., Janousch M., Bargar J. R., Persson P. and Bernier–Latmani R. (2014). The product of microbial uranium reduction includes multiple species with U (IV)–phosphate coordination. *Geochimica et Cosmochimica Acta* 131, 115–27.
- [9] Alqadami A. A., Naushad M., Alothman Z. A. and Ghfar A. A. (2017). Novel metal–organic framework (MOF) based composite material for the sequestration of U (VI) and Th (IV) metal ions from aqueous environment. *ACS Applied Materials & Interfaces* 9(41), 36026–37.
- [10] Amphlett J. T., Ogden M. D., Foster R. I., Syna N., Soldenhoff K. and Sharrad C. A. (2018). Polyamine functionalised ion exchange resins: Synthesis, characterisation and uranyl uptake. *Chemical Engineering Journal* 334, 1361–70.
- [11] Åström M. E., Peltola P., Rönneck P., Lavergren U., Bergbäck B., Tarvainen T., Backman B. and Salminen R. (2009). Uranium in surface and groundwaters in Boreal Europe. *Geochemistry: Exploration, Environment, Analysis* 9(1), 51–62.
- [12] Ataei M., Fadaei A., Mardani G. and Sedehi M. (2020). Removal of 17β–Estradiol (E2) from Aqueous Solutions Using Potassium Permanganate Combined with Ultraviolet (KMnO4/UV). *International Journal of Chemical Engineering* 2020.
- [13] Atkins M. L., Santos I. R., Perkins A. and Maher D. T. (2016). Dissolved radon and uranium in groundwater in a potential coal seam gas development region (Richmond River Catchment, Australia). *Journal of environmental radioactivity* 154, 83–92.
- [14] Aziz A., Jan S., Waqar F., Mohammad B., Hakim M. and Yawar W. (2010). Selective ion exchange separation of uranium from concomitant impurities in uranium materials and subsequent determination of the impurities by ICP–OES. *Journal of Radioanalytical and Nuclear Chemistry* 284(1), 117–21.
- [15] Baeza A., Fernandez M., Herranz M., Legarda F., Miro C. and Salas A. (2006). Removing uranium and radium from a natural water. *Water, air, and soil pollution* 173(1), 57–69.
- [16] Barescut J., Lariviere D., Stocki T., Turtiainen T., Muikku M., Vesterbacka P. and Heikkinen T. (2011). Uranium and 226Ra in drinking water supplied by Finnish waterworks. *Radioprotection* 46(6), S255–S63.
- [17] Barton C. S., Stewart D. I., Morris K. and Bryant D. E. (2004). Performance of three resin–based materials for treating uranium–contaminated groundwater within a PRB. *Journal of Hazardous Materials* 116(3), 191–204.
- [18] Berisha F. and Goessler W. (2013). Uranium in Kosovo’s drinking water. *Chemosphere* 93(9), 2165–70.
- [19] Bhat S. V., Melo J., Chaugule B. and D’souza S. (2008). Biosorption characteristics of uranium (VI) from aqueous medium onto *Catenella repens*, a red alga. *Journal of Hazardous Materials* 158(2–3), 628–35.
- [20] Bowman R. S. (1997). Aqueous environmental geochemistry. In: Wiley Online Library.
- [21] Burkitbayev M., Uralbekov B., Nazarkulova S., Matveyeva I. and Vintró L. L. (2012). Uranium series radionuclides in surface waters from the Shu river (Kazakhstan). *Journal of Environmental Monitoring* 14(4), 1189–94.
- [22] Campbell E. L., Levitskaia T. G., Fujimoto M. S., Holfeltz V. E., Chatterjee S. and Hall G. B. (2018). Analysis of Uranium Ion Exchange Resin from the 200 West Pump–and–Treat Facility, Pacific Northwest National Lab. (PNNL), Richland, WA (United States).
- [23] Carvajal D. A., Katsenovich Y. P. and Lagos L. E. (2012). The effects of aqueous bicarbonate and calcium ions on uranium biosorption by *Arthrobacter* G975 strain. *Chemical Geology* 330, 51–9.
- [24] Chen J. (2018). A summary of natural radionuclides in Canadian public water supply systems. *Radiat. Environ. Med.* 7, 9–12.
- [25] Cho B. W. and Choo C. O. (2019). Geochemical behavior of uranium and radon in groundwater of Jurassic granite area, Icheon, Middle Korea. *Water* 11(6), 1278.
- [26] Cooper P., Nie J., Larson S. L., Ballard J. H., Knotek–Smith H. M., Celik A., Dasari S., Zhu X. and Han F. X. (2021). Uranium Adsorption on Three Nanohydroxyapatites Under Various Biogeochemical Conditions. *Water, Air, & Soil Pollution* 232(9), 1–10.
- [27] Costa M., Pereira A., Neves L. and Ferreira A. (2017). Potential human health impact of groundwater in non–exploited uranium ores: The case of Horta da Vilarica (NE Portugal). *Journal of Geochemical Exploration* 183, 191–6.
- [28] Dai Z., Sun Y., Zhang H., Ding D. and Li L. (2020). Photocatalytic reduction of U (VI) in wastewater by mGO/g–C3N4 nanocomposite under visible LED light irradiation. *Chemosphere* 254, 126671.
- [29] Deng H., Li Z.–j., Wang L., Yuan L.–y., Lan J.–h., Chang Z.–y., Chai Z.–f. and Shi W.–q. (2019). Nanolayered Ti3C2 and SrTiO3 composites for photocatalytic reduction and removal of uranium (VI). *ACS Applied Nano Materials* 2(4), 2283–94.
- [30] Ding L., Liao J. and Zhang Y. (2021). Adsorption performance and mechanism of Al2O3 aerogels towards aqueous U (VI) using template synthesis technology. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 612, 125980.

- [31] Dinis M. d. L. and Fiúza A. (2021). Mitigation of Uranium Mining Impacts—A Review on Groundwater Remediation Technologies. *Geosciences* 11(6), 250.
- [32] Directive C. (2013). Council Directive 2013/51/EURATOM of 22 October 2013. Laying down requirements for the protection of the health of the general public with regard to radioactive substances in water intended for human consumption. *Official Journal of the European Union* 7(2013), 56.
- [33] Duggal V., Sharma S. and Singh A. (2021). Risk assessment of uranium in drinking water in Hisar district of Haryana, India. *Water Supply* 21(1), 249–61.
- [34] Edition F. (2011). Guidelines for drinking–water quality. *WHO chronicle* 38(4), 104–8.
- [35] El–Maghrabi H. H., Abdelmaged S. M., Nada A. A., Zahran F., Abd El–Wahab S., Yahea D., Hussein G. and Atrees M. (2017). Magnetic graphene based nanocomposite for uranium scavenging. *Journal of Hazardous Materials* 322, 370–9.
- [36] Evans S. F., Ivancevic M. R., Yan J., Naskar A. K., Levine A. M., Lee R. J., Tsouris C. and Paranthaman M. P. (2019). Magnetic adsorbents for selective removal of selenite from contaminated water. *Separation Science and Technology* 54(13), 2138–46.
- [37] Fadaei A. (2022). Comparison of removal techniques of manganese from water and waste water. *Annals of the Faculty of Engineering Hunedoara–International Journal of Engineering*(3).
- [38] Fadaei A. and Amiri M. (2013). The association between applying sodium fluoride mouthwash and decayed missed filled teeth (DMFT) index in elementary students of Charharmahal and Bakhtiari province, Iran. *World Applied Sciences Journal* 24(2), 140–5.
- [39] Fan F.–L., Qin Z., Bai J., Rong W.–D., Fan F.–Y., Tian W., Wu X.–L., Wang Y. and Zhao L. (2012). Rapid removal of uranium from aqueous solutions using magnetic Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub> composite particles. *Journal of environmental radioactivity* 106, 40–6.
- [40] Favre–Réguillon A., Lebizut G., Murat D., Foos J., Mansour C. and Draye M. (2008). Selective removal of dissolved uranium in drinking water by nanofiltration. *Water Research* 42(4–5), 1160–6.
- [41] Fawell J., Bailey K., Chilton J., Dahi E. and Magara Y. (2006). Fluoride in drinking–water. IWA publishing.
- [42] Frengstad B. S. and Banks D. (2014). Uranium distribution in groundwater from fractured crystalline aquifers in Norway. *Fractured Rock Hydrogeology, International Association of Hydrogeologists Selected Papers* 20, 257–76.
- [43] Frisbie S. H., Mitchell E. J. and Sarkar B. (2013). World Health Organization increases its drinking–water guideline for uranium. *Environmental Science: Processes & Impacts* 15(10), 1817–23.
- [44] Gans I. (1985). Natural radionuclides in mineral waters. *Science of the total environment* 45, 93–9.
- [45] Gerber U., Hübner R., Rossberg A., Krawczyk–Bärsch E. and Merroun M. L. (2018). Metabolism–dependent bioaccumulation of uranium by *Rhodosporidium toruloides* isolated from the flooding water of a former uranium mine. *PLoS One* 13(8), e0201903.
- [46] Godoy J. M., Ferreira P. R., Souza E. M. d., Silva L. I. d., Bittencourt I. and Fraifeld F. (2019). High uranium concentrations in the groundwater of the Rio de Janeiro State, Brazil, Mountainous Region. *Journal of the Brazilian Chemical Society* 30, 224–33.
- [47] Gong J., Xie Z., Wang B., Li Z., Zhu Y., Xue J. and Le Z. (2021). Fabrication of g–C<sub>3</sub>N<sub>4</sub>–based conjugated copolymers for efficient photocatalytic reduction of U (VI). *Journal of Environmental Chemical Engineering* 9(1), 104638.
- [48] Guo Y., Li L., Li Y., Li Z., Wang X. and Wang G. (2016). Adsorption and photocatalytic reduction activity of uranium (VI) on zinc oxide/rectorite composite enhanced with methanol as sacrificial organics. *Journal of Radioanalytical and Nuclear Chemistry* 310(2), 883–90.
- [49] Hakonson–Hayes A. C., Fresquez P. and Whicker F. (2002). Assessing potential risks from exposure to natural uranium in well water. *Journal of environmental radioactivity* 59(1), 29–40.
- [50] Han Y., Lee J., Kim C., Park J., Lee M. and Yang M. (2021). Uranium Rhizofiltration by *Lactuca sativa*, *Brassica campestris* L., *Raphanus sativus* L., *Oenanthe javanica* under Different Hydroponic Conditions. *Minerals* 11(1), 41.
- [51] Hoyer M. (2017). Post–Mining Water Treatment: Nanofiltration of Uranium–Contaminated Drainage; Experiments and Modeling. Technische Universitaet Berlin (Germany).
- [52] Hoyer M., Zabelt D., Steudtner R., Brendler V., Haseneder R. and Repke J.–U. (2014). Influence of speciation during membrane treatment of uranium contaminated water. *Separation and Purification Technology* 132, 413–21.
- [53] Hu L., Yan X.–W., Zhang X.–J. and Shan D. (2018). Integration of adsorption and reduction for uranium uptake based on SrTiO<sub>3</sub>/TiO<sub>2</sub> electrospun nanofibers. *Applied Surface Science* 428, 819–24.
- [54] Huang Y., Su M., Chen D., Zhu L., Pang Y. and Chen Y. (2021). Highly–efficient and easy separation of hexahedral sodium dodecyl sulfonate/δ–FeOOH colloidal particles for enhanced removal of aqueous thallium and uranium ions: synergistic effect and mechanism study. *Journal of Hazardous Materials* 402, 123800.
- [55] Jiang X.–H., Xing Q.–J., Luo X.–B., Li F., Zou J.–P., Liu S.–S., Li X. and Wang X.–K. (2018). Simultaneous photoreduction of Uranium (VI) and photooxidation of Arsenic (III) in aqueous solution over g–C<sub>3</sub>N<sub>4</sub>/TiO<sub>2</sub> heterostructured catalysts under simulated sunlight irradiation. *Applied Catalysis B: Environmental* 228, 29–38.
- [56] Kahle S. C., Welch W. B., Tecca A. E. and Eliason D. M. (2018). Uranium concentrations in groundwater, northeastern Washington, Report 2329–132X, US Geological Survey.
- [57] Katsoyiannis I. and Zouboulis A. (2013). Removal of uranium from contaminated drinking water: a mini review of available treatment methods. *Desalination and water treatment* 51(13–15), 2915–25.
- [58] Kenney J. P., Ellis T., Nicol F. S., Porter A. E. and Weiss D. J. (2018). The effect of bacterial growth phase and culture concentration on U (VI) removal from aqueous solution. *Chemical Geology* 482, 61–71.
- [59] Khedr M. G. (2009). Nanofiltration and low energy reverse osmosis for rejection of radioactive isotopes and heavy metal cations from drinking water sources. *Desalin. Water Treat* 2(1), 342–50.
- [60] Khedr M. G. (2013). Radioactive contamination of groundwater, special aspects and advantages of removal by reverse osmosis and nanofiltration. *Desalination* 321, 47–54.
- [61] Kim G.–N., Shon D.–B., Park H.–m., Choi W.–K. and Lee K.–W. (2011). The development of precipitation–filtering technology for uranium electrokinetic leachate. *Separation and Purification Technology* 79(2), 144–50.
- [62] Kim J., Tsouris C., Mayes R. T., Oyola Y., Saito T., Janke C. J., Dai S., Schneider E. and Sachde D. (2013). Recovery of uranium from seawater: a review of current status and future research needs. *Separation Science and Technology* 48(3), 367–87.
- [63] Kim Y. K., Lee S., Ryu J. and Park H. (2015). Solar conversion of seawater uranium (VI) using TiO<sub>2</sub> electrodes. *Applied Catalysis B: Environmental* 163, 584–90.
- [64] Kirby M. E., Watson J. S., Najorka J., Kenney J. P. L., Krevor S. and Weiss D. J. (2020). Experimental study of pH effect on uranium (U(VI)) particle formation and transport through quartz sand in alkaline 0.1 M sodium chloride solutions. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 592, 124375.
- [65] Kolhe N., Zinjarde S. and Acharya C. (2020). Impact of uranium exposure on marine yeast, *Yarrowia lipolytica*: insights into the yeast strategies to withstand uranium stress. *Journal of Hazardous Materials* 381, 121226.
- [66] Kryvoruchko A. P., Yurlova L. Y., Atamanenko I. D. and Kornilovich B. Y. (2004). Ultrafiltration removal of U (VI) from contaminated water. *Desalination* 162, 229–36.

- [67] Kuncham K., Nair S., Durani S. and Bose R. (2017). Efficient removal of uranium (VI) from aqueous medium using ceria nanocrystals: an adsorption behavioural study. *Journal of Radioanalytical and Nuclear Chemistry* 313(1), 101–12.
- [68] Lemons B., Khaing H., Ward A. and Thakur P. (2018). A rapid method for the sequential separation of polonium, plutonium, americium and uranium in drinking water. *Applied Radiation and Isotopes* 136, 10–7.
- [69] Liao Y., Wang M. and Chen D. (2019). Electrosorption of uranium (VI) by highly porous phosphate–functionalized graphene hydrogel. *Applied Surface Science* 484, 83–96.
- [70] Liu W., Zhao X., Wang T., Zhao D. and Ni J. (2016). Adsorption of U (VI) by multilayer titanate nanotubes: effects of inorganic cations, carbonate and natural organic matter. *Chemical Engineering Journal* 286, 427–35.
- [71] Liu X., Du P., Pan W., Dang C., Qian T., Liu H., Liu W. and Zhao D. (2018a). Immobilization of uranium (VI) by niobate/titanate nanoflakes heterojunction through combined adsorption and solar–light–driven photocatalytic reduction. *Applied Catalysis B: Environmental* 231, 11–22.
- [72] Liu Y.–H., Wang Y.–Q., Zhang Z.–B., Cao X.–H., Nie W.–B., Li Q. and Hua R. (2013). Removal of uranium from aqueous solution by a low cost and high–efficient adsorbent. *Applied Surface Science* 273, 68–74.
- [73] Liu Z., Liu D., Cai Z., Wang Y. and Zhou L. (2018b). Synthesis of new type dipropyl imide chelating resin and its potential for uranium (VI) adsorption. *Journal of Radioanalytical and Nuclear Chemistry* 318(2), 1219–27.
- [74] Ma W., Gao B., Guo Y., Sun Z., Zhang Y., Chen G., Zhu X. and Zhang C. (2020). Occurrence and distribution of uranium in a hydrological cycle around a uranium mill tailings Pond, Southern China. *International journal of environmental research and public health* 17(3), 773.
- [75] Matteoda E., Blarasin M., Lutri V., Giacobone D., Maldonado L., Quinodoz F. B., Albo J. G. and Cabrera A. (2019). Uranium In Groundwater In The Sedimentary Aquifer Of The Eastern Sector Of Valle De La Cruz, Córdoba, Argentina.
- [76] Mishra V., Sureshkumar M., Gupta N. and Kaushik C. (2017). Study on sorption characteristics of uranium onto biochar derived from eucalyptus wood. *Water, Air, & Soil Pollution* 228(8), 1–14.
- [77] Mullett M., Fornarelli R. and Ralph D. (2014). Nanofiltration of mine water: impact of feed pH and membrane charge on resource recovery and water discharge. *Membranes* 4(2), 163–80.
- [78] Nariyan E., Sillanpää M. and Wolkersdorfer C. (2018). Uranium removal from Pyhäsalmi/Finland mine water by batch electrocoagulation and optimization with the response surface methodology. *Separation and Purification Technology* 193, 386–97.
- [79] NHMRC N. (2011). Australian drinking water guidelines paper 6 national water quality management strategy. National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra, 5–7.
- [80] Petersková M., Valderrama C., Gibert O. and Cortina J. L. (2012). Extraction of valuable metal ions (Cs, Rb, Li, U) from reverse osmosis concentrate using selective sorbents. *Desalination* 286, 316–23.
- [81] Phillips D. H., Gu B., Watson D. B. and Parmele C. (2008). Uranium removal from contaminated groundwater by synthetic resins. *Water Research* 42(1–2), 260–8.
- [82] Pontér S., Rodushkin I., Engström E., Rodushkina K., Paulukat C., Peinerud E. and Widerlund A. (2021). Early diagenesis of anthropogenic uranium in lakes receiving deep groundwater from the Kiruna mine, northern Sweden. *Science of the total environment* 793, 148441.
- [83] Prat O., Vercouter T., Ansoborlo E., Fichet P., Perret P., Kurttio P. i. and Salonen L. (2009). Uranium speciation in drinking water from drilled wells in southern Finland and its potential links to health effects. *Environmental science & technology* 43(10), 3941–6.
- [84] Protection R. (2007). ICRP publication 103. *Ann ICRP* 37(2.4), 2.
- [85] Riegel M. (2017). Sorption of Natural Uranium on Weakly Basic Anion Exchangers. *Solvent Extraction and Ion Exchange* 35(5), 363–75.
- [86] Rohith S., Ramanan K. K., Srinivas N. S. and Jegadeesan G. B. (2020). Fe–Ni–doped graphene oxide for uranium removal—kinetics and equilibrium studies. *Water, Air, & Soil Pollution* 231(8), 1–17.
- [87] Saini A. S. and Melo J. S. (2013). Biosorption of uranium by melanin: kinetic, equilibrium and thermodynamic studies. *Bioresource technology* 149, 155–62.
- [88] Salomone V. N., Meichtry J. M. and Litter M. I. (2015). Heterogeneous photocatalytic removal of U (VI) in the presence of formic acid: U (III) formation. *Chemical Engineering Journal* 270, 28–35.
- [89] Sastri V. and Ashbrook A. (1976). Reverse osmosis performance of cellulose acetate membranes in the separation of uranium from dilute solutions. *Separation Science and Technology* 11(4), 361–76.
- [90] Schumann R. R., Zielinski R. A., Otton J. K., Pantea M. P. and Orem W. H. (2017). Uranium delivery and uptake in a montane wetland, north–central Colorado, USA. *Applied Geochemistry* 78, 363–79.
- [91] Sharma T., Sharma A., Kaur I., Mahajan R., Litoria P., Sahoo S. and Bajwa B. (2019). Uranium distribution in groundwater and assessment of age dependent radiation dose in Amritsar, Gurdaspur and Pathankot districts of Punjab, India. *Chemosphere* 219, 607–16.
- [92] Shen J. and Schäfer A. (2014). Removal of fluoride and uranium by nanofiltration and reverse osmosis: a review. *Chemosphere* 117, 679–91.
- [93] Sohrabi N. and Amiri V. (2018). An evaluation of the distribution and behavior of uranium in Urmia aquifer. *Iran–Water Resources Research* 14(3), 198–215.
- [94] Somboon S., Inoue K., Fukushi M., Tsuruoka H., Shimizu H., Kasar S., Arae H., Kavasi N. and Sahoo S. (2019). Distribution of uranium in Japanese river waters determined with inductively coupled plasma mass spectrometry. *Journal of Radioanalytical and Nuclear Chemistry* 319(3), 1307–14.
- [95] Song S., Zhang S., Huang S., Zhang R., Yin L., Hu Y., Wen T., Zhuang L., Hu B. and Wang X. (2019). A novel multi–shelled Fe<sub>3</sub>O<sub>4</sub>@ MnOx hollow microspheres for immobilizing U (VI) and Eu (III). *Chemical Engineering Journal* 355, 697–709.
- [96] Sorg T. J. (1988). Methods for removing uranium from drinking water. *Journal–American Water Works Association* 80(7), 105–11.
- [97] Stalder E., Blanc A., Haldimann M. and Dudler V. (2012). Occurrence of uranium in Swiss drinking water. *Chemosphere* 86(6), 672–9.
- [98] Sun Y., Lu S., Wang X., Xu C., Li J., Chen C., Chen J., Hayat T., Alsaedi A. and Alharbi N. S. (2017). Plasma–facilitated synthesis of amidoxime/carbon nanofiber hybrids for effective enrichment of <sup>238</sup>U (VI) and <sup>241</sup>Am (III). *Environmental science & technology* 51(21), 12274–82.
- [99] Thivya C., Chidambaram S., Tirumalesh K., Prasanna M. V., Thilagavathi R. and Nepolian M. (2014). Occurrence of the radionuclides in groundwater of crystalline hard rock regions of central Tamil Nadu, India. *Journal of Radioanalytical and Nuclear Chemistry* 302(3), 1349–55.
- [100] Tolkou A. K., Katsoyiannis I. A. and Zouboulis A. I. (2020). Removal of arsenic, chromium and uranium from water sources by novel nanostructured materials including graphene–based modified adsorbents: A mini review of recent developments. *Applied Sciences* 10(9), 3241.
- [101] Tomé F. V., Rodríguez P. B. and Lozano J. (2008). Elimination of natural uranium and <sup>226</sup>Ra from contaminated waters by rhizofiltration using *Helianthus annuus* L. *Science of the total environment* 393(2–3), 351–7.
- [102] Tripathi S., Roy A., Nair S., Durani S. and Bose R. (2018). Removal of U (VI) from aqueous solution by adsorption onto synthesized silica and zinc silicate nanotubes: equilibrium and kinetic aspects with application to real samples. *Environmental nanotechnology, monitoring & management* 10, 127–39.
- [103] Ullah H., Liu G., Yousaf B., Ali M. U., Irshad S., Abbas Q. and Ahmad R. (2019). A comprehensive review on environmental transformation of selenium: recent advances and research perspectives. *Environmental geochemistry and health* 41(2), 1003–35.

- [104] Uralbekov B., Smodis B. and Burkitbayev M. (2011). Uranium in natural waters sampled within former uranium mining sites in Kazakhstan and Kyrgyzstan. *Journal of Radioanalytical and Nuclear Chemistry* 289(3), 805–10.
- [105] USEPA W. (2018). Edition of the Drinking Water Standards and Health Advisories Tables: United States Environmental Protection Agency. Office of Water.
- [106] Vance R., Price R. and Barthel F. (2006). Recent activities of the joint Nuclear Energy Agency (NEA)/International Atomic Energy Agency (IAEA) Uranium Group.
- [107] Wagner S. E., Burch J. B., Bottai M., Puett R., Porter D., Bolick–Aldrich S., Temples T., Wilkerson R. C., Vena J. E. and Hébert J. R. (2011). Groundwater uranium and cancer incidence in South Carolina. *Cancer Causes & Control* 22(1), 41–50.
- [108] Wang F., Liu Q., Li R., Li Z., Zhang H., Liu L. and Wang J. (2016). Selective adsorption of uranium (VI) onto prismatic sulfides from aqueous solution. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 490, 215–21.
- [109] Wang F., Wang X., Jiang Y., Niu Z., Wu W. and Zhang H. (2020a). Study of adsorption performance and adsorption mechanism for U (VI) ion on modified polyacrylonitrile fibers. *Journal of Radioanalytical and Nuclear Chemistry* 323(1), 365–77.
- [110] Wang G., Zhen J., Zhou L., Wu F. and Deng N. (2015a). Adsorption and photocatalytic reduction of U (VI) in aqueous TiO<sub>2</sub> suspensions enhanced with sodium formate. *Journal of Radioanalytical and Nuclear Chemistry* 304(2), 579–85.
- [111] Wang J., Liu J., Li H., Song G., Chen Y., Xiao T., Qi J. and Zhu L. (2012). Surface water contamination by uranium mining/milling activities in northern Guangdong province, China. *CLEAN–Soil, Air, Water* 40(12), 1357–63.
- [112] Wang J., Wang Y., Wang W., Ding Z., Geng R., Li P., Pan D., Liang J., Qin H. and Fan Q. (2020b). Tunable mesoporous g–C<sub>3</sub>N<sub>4</sub> nanosheets as a metal–free catalyst for enhanced visible–light–driven photocatalytic reduction of U (VI). *Chemical Engineering Journal* 383, 123193.
- [113] Wang W. Q., Brackhage C., Bäuker E. and Dudel E. G. (2015b). Rhizofiltration of U by plant root surfaces in a tailing wetland. In: *Uranium–Past and Future Challenges*, Springer, pp. 497–508.
- [114] Wazne M., Meng X., Korfiatis G. P. and Christodoulatos C. (2006). Carbonate effects on hexavalent uranium removal from water by nanocrystalline titanium dioxide. *Journal of Hazardous Materials* 136(1), 47–52.
- [115] White C. and Gadd G. M. (1990). Biosorption of radionuclides by fungal biomass. *Journal of Chemical Technology & Biotechnology* 49(4), 331–43.
- [116] Wu Y., Pang H., Yao W., Wang X., Yu S., Yu Z. and Wang X. (2018). Synthesis of rod–like metal–organic framework (MOF–5) nanomaterial for efficient removal of U (VI): batch experiments and spectroscopy study. *Science bulletin* 63(13), 831–9.
- [117] Xie J., Lin J. and Zhou X. (2018). pH–dependent microbial reduction of uranium (VI) in carbonate–free solutions: UV–vis, XPS, TEM, and thermodynamic studies. *Environmental Science and Pollution Research* 25(22), 22308–17.
- [118] Xie J., Lv R., Peng H., Fan J., Tao Q., Dai Y., Zhang Z., Cao X. and Liu Y. (2020). Phosphate functionalized poly (vinyl alcohol)/poly (acrylic acid)(PVA/PAA): an electrospinning nanofiber for uranium separation. *Journal of Radioanalytical and Nuclear Chemistry* 326(1), 475–86.
- [119] Xu Y., Ke G., Yin J., Lei W. and Yang P. (2019). Synthesis of thiol–functionalized hydrotalcite and its application for adsorption of uranium (VI). *Journal of Radioanalytical and Nuclear Chemistry* 319(3), 791–803.
- [120] Yang A., Wang Z. and Zhu Y. (2020). Facile preparation and adsorption performance of low–cost MOF@ cotton fibre composite for uranium removal. *Scientific Reports* 10(1), 1–10.
- [121] Yang L. X., Feng X. F., Yin W. H., Tao Y., Wu H. Q., Li J. Q., Ma L. F. and Luo F. (2018). Metal–organic framework containing both azo and amide groups for effective U (VI) removal. *Journal of Solid State Chemistry* 265, 148–54.
- [122] Yang M., Jawitz J. W. and Lee M. (2015). Uranium and cesium accumulation in bean (*Phaseolus vulgaris* L. var. *vulgaris*) and its potential for uranium rhizofiltration. *Journal of environmental radioactivity* 140, 42–9.
- [123] Yekta S., Sadeghi M., Ghaedi H. and Shahabfar N. (2016). Removal of uranium (U (VI)) ions using NiO NPs/Ag–clinoptilolite zeolite composite adsorbent from drinking water: equilibrium, kinetic and thermodynamic studies. *Int. J. Bio–Inorg. Hybr. Nanomater* 5(4), 279–95.
- [124] Yoon Y. Y., Cho S. Y., Lee K. Y., Ko K. S. and Ha K. (2013). Radiochemical determination of uranium and radium isotope in natural water using liquid scintillation counter. *Journal of Radioanalytical and Nuclear Chemistry* 296(1), 397–402.
- [125] Yu C., Berger T., Drake H., Song Z., Peltola P. and Åström M. E. (2019). Geochemical controls on dispersion of U and Th in Quaternary deposits, stream water, and aquatic plants in an area with a granite pluton. *Science of the total environment* 663, 16–28.
- [126] Yu J. and Wang J. (2016). Removal of uranium from aqueous solution by carbon nanotubes. *Health physics* 111(4), 367–73.
- [127] Yurlova L. Y. (2020). Removal of U (VI) from Waters by Ultrafiltration Using Dynamic Membranes Formed From Montmorillonite and the Layered Double Hydroxide Zn–Al–EDTA. *Journal of Water Chemistry and Technology* 42(2), 120–5.
- [128] Zamora M. L., Zielinski J., Meyerhof D., Falcomer R., Moodie G., Capello K. and Tracy B. (2004). Chronic exposure of a Canadian Aboriginal Community to uranium in drinking water: Chemical Toxicity and Radiation Dose. *Radiation Protection Bureau, Health Canada* 775.
- [129] Zhang Y.–J., Lan J.–H., Wang L., Wu Q.–Y., Wang C.–Z., Bo T., Chai Z.–F. and Shi W.–Q. (2016). Adsorption of uranyl species on hydroxylated titanium carbide nanosheet: A first–principles study. *Journal of Hazardous Materials* 308, 402–10.
- [130] Zheng X., Shen Y., Wang X. and Wang T. (2018). Effect of pH on uranium (VI) biosorption and biomineralization by *Saccharomyces cerevisiae*. *Chemosphere* 203, 109–16.



ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN–L 1584 – 2665

copyright © University POLITEHNICA Timisoara, Faculty of Engineering Hunedoara,

5, Revolutiei, 331128, Hunedoara, ROMANIA

<http://annals.fih.upt.ro>