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Review on Decontamination Manners of Radioactive Liquids

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Abstract Practicing in nuclear facilities emits significant amounts of radioactive waste. Additionally, conflicts and tensions have always existed among the international nuclear order. In this regard, the latest problem is the Russo-Ukrainian conflict, in which ordinary weapons have been solely used since February 2022 until now. However, this tension may result in nuclear trends of multi-face undertones. In addition, due to the location of the Middle East region on the seismic line, the Turkish earthquake has recently occurred at 430 km from the Akkuyu nuclear facility. For emergency preparedness and response, there has been an urgent need to reveal and review the literature dealing with the decontamination methods used to purify radioactive liquids generated during practice for nuclear applications. Such liquids have a considerable volume of low, intermediate, or high radioactivity. In particular, the characteristics, challenges, and effects of radioactive liquids were overviewed. In this context, the activities of precipitation, adsorption, ion exchange, membrane separation, vaporization concentration, biotechnology, and photocatalysis were introduced as active decontamination techniques for radioactive liquids. Specifically, the features and shortcomings of each method as single and combined systems were discussed. The improvement directions of futuristic treatment works have been prospected. Radioactive liquid treatment methods are budding, and hence, studies and information should be increased. These methods draw considerable attention due to the rapidly evolving requirements for recovering radiation wastes. Particularly, the technique must consider high efficiency, produced sludge intensity, handling cost, safety requirements, and reliability. In addition, the combination system involving a series of techniques will be the important futuristic expansion trend of radioactive liquids treatment. This system requires a relatively high cost. However, it has robust performance for minimizing nuclear waste.

Keywords Radioactive liquids · Decontamination · Adsorption · Membrane separation · Vaporization concentration

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1 Introduction

Since fossil fuels are considered nonrenewable, and there is a finite number of renewable energy, nuclear power has increasingly become an alternative origin (Shirizadeh & Quirion, 2021). Owing to the global evolution of nuclear energy facilities, a massive quantity of rad-waste involving liquids was produced during different practices (Holt et al., 2022). In this context, radioactive waste passes many stages during its life. Radioactively contaminated waste's pre-disposal consists of collecting, segregating, treating, conditioning, storing, and transporting to the definitive disposal landfill. To this end, categorization has plenty of benefits during each stage, from the point of generation passing by pre-disposal management to the final decision for disposal. This categorization has been taken from various aspects, such as radiation protection, the physical and chemical nature of the generated waste, demands of waste handling, and regulatory challenges (Atomic, 2011). The radiation emissions level from waste usually significantly impacts specifying management trends and shielding calculations (Amin et al., 2019). Therefore, the international categorization options depend on radioactivity levels and radionuclide content's half-life. This categorization aims to overview a general structure for categorizing the radioactive elements. In particular, it considers the safety in the long term and, ultimately, the relevance of disposal options. Moreover, it helps the progression and execution of suitable radioactive waste management strategies, promoting communication and facilitating exchangeable nuclear data among countries (Natarajan et al., 2020). The categorization system sorted the radioactive waste into exempt (EW), which can be conventionally managed; waste of low and medium hazard (LILW), which is sub-categorized to short- and long-lived waste; and waste of high-level (HLW), which requires special handling and management. Table 1 tabulates the types and properties of each waste class (Adeola et al., 2022; Agency, 1999).

Radioactive liquids are made through the work in facilities dealing with nuclear science and the implementation of radionuclides in atomic energy fields. The complexity and the degree of contamination hazard of the produced waste rely on the practiced operation. Dissolved radioisotopes are movable in the ambient. If not sufficiently handled, they may percolate to aquatic life via surface water and groundwater, which will automatically raise the hazard of

Table 1 Classification of radioactively contaminated waste (Agency, 1999)

Waste class	Principal characteristics
EW (exempt waste)	Waste has trivial concentrations of radioactive elements. Therefore, radiation protection provisions are not necessary. It can be recycled or disposed of in conventional landfills. It can be exempted from regulatory oversight and does not necessitate any additional examination from a regulatory standpoint. It has an annual dose of up to 0.01 mSv
LILW (low- and intermediate-level waste)	"Low-level waste" describes radioactive elements that can be handled and transported without shielding. "Intermediate-level waste" refers to the radioactive elements that require shielding but do not require much or any provisions for preventing the released heat. The emitted heat is up to 2 kW/m^3
LILW-SL (low- and intermediate-level waste-short-lived radionuclides)	This waste consists of radioactive elements with short half-lives and activity concentrations that exceed the clearance thresholds. It can be kept until its activity decreases below the levels required for clearance, enabling it to be managed as regular waste. It has Alpha emissions with long-live of less than 4 kBq/g in one pack, and the average is 0.4 kBq/g for each package
LILW-LL (low- and intermediate-level waste-long-lived radionuclides)	Concentrations of Alpha emissions with long-lived are greater than those limited for short-lived waste
HLW (high-level waste)	This type refers to waste with significant concentrations of short- and long-lived radioactive elements compared to ILW. It needs a high level of isolation from the ambient. It is required to provide safety in the long term. It disposes of deep geological areas containing engineered barriers. The emitted heat exceeds 2 kW/m^3, and the concentrations of radionuclides with long-lived are greater than those limited for short-lived waste

personal exposure to radioisotopes (Frieß & Liebert, 2022). Discharging unhandled radioactive liquids into the surrounding ambient will be a damage source to humans and other creatures (Contis & Foley Jr, 2015). Therefore, radioactive liquid handling has been a concentration of social concern, and the central focus is reducing its environmental and public health hazards.

Moreover, the psychological pressure resulting from radioactivity to the public is mitigated. In this regard, decontamination is an effective practice in controlling radioactive releases. It aims to decrease the formed waste amount to increase safety and cost-saving for the subsequent phases. After the decontamination practice, the waste may be in one of two situations. The first situation is waste with a large volume that meets the permissible levels for conventional waste disposal. The second situation is a waste with a low volume containing radionuclide concentrations slightly exceeding the allowable levels. This waste can be kept for a short period to dissipate its radioactivity, and it is disposed of as ordinary waste (waste not on the inventory of hazardous waste) (Abdel-Rahman et al., 2011). The fundamental radionuclides in radioactive liquids are uranium and traces of radium and thorium (Matsuo & Nishi, 2000). Compared with other pollutants, contaminants with radioactive hazards have a significantly longer half-life. For example, the U-238 half-life is about 4500 million years, has high toxicity, and has stability for an extended period. To inhibit the produced radioactive wastes from interacting with the environment, which may cause damage to the ecological formation or public health, and to secure the sustained evolution of atomic power, it is unavoidable to give particular interest to the handling and discharge of radioactive liquids. As a result, the main point that requires resolving is efficiently handling radioactive liquids with minimum costs and needs. The radioactive liquids' properties and origin are listed in Table 2 (Jiménez-Reyes et al., 2021; Ma et al., 2023; Phillip et al., 2023; Rahman et al., 2011).

The wastewater purification process is executed to remove the contaminants or to transform them into nontoxic elements. This process is categorized into (1) the separation method removes impurities from liquids through the influence of diverse forces. Generally, the chemical composition of the impurities is not changed during the operation flow. (2) The transformation method alters the chemical structure of contaminants by chemical reactions or biochemical impacts. Contaminants are converted to removable materials to separate them. (3) The dilution method neither separates the contaminants nor alters their chemical composition. Through dilution and mixing, two aspects are mostly followed (Nie et al., 2021): the first is diluting and removing very low-level radioactivity liquids to meet the permissible levels, and the second is solidification (the process of evaporation then calcination of the waste material to produce a granular or a solid material) (Fuks et al., 2022) and isolation for a long-term period from the environment to allow natural decay for high-, intermediate-, and low-level radioactivity liquids. In contrast, calculating the decontamination coefficient (DF) and the concentration coefficient (CF) for decontaminating radioactive liquids is recommendable (Pabby et al., 2022). More specifically, the DF is the ratio between the radioactivity intensity and the mass concentration before and after decontamination (Zhu et al., 2020), and the CF is the ratio between the volume of the radioactive liquids before decontamination and the size of the residues after treatment (Ma et al., 2023). The DF clarifies the reduction in radioactivity level. A higher CF refers to more size reduction of the radioactive liquids, which results in further encapsulation.

Several reasons arise from time to time to necessitate a review of the literature on decontamination methods for liquid waste, such as conflicts and tensions among the international nuclear order. One of the latest issues is the Russo-Ukrainian conflict, which has solely used ordinary weapons since February 2022 until now (Haq et al., 2022). In this regard, tactical nuclear tools are manufactured for use in battles, for which the damages may be tens of millions of tons, more volume than the disaster at Hiroshima (Ciottone & Alexander, 2024). While they are typically less vigorous than strategic nuclear bombs, there is no specific upper limit. However, the Russo-Ukrainian conflict may have nuclear trends of multiface undertones. It brings up significant issues regarding the workings of nuclear restrain, and it brings attention to other possible futuristic crises elsewhere in the world. In addition to the growing fears of nature's fury, the most important issue is the occurrence of the Middle East region on the seismic line. The latest crisis in this context is the Turkish earthquake, whose epicenter is 430 km from the Akkuyu Nuclear Facility (Yuan et al., 2023). Although the atomic explosion may not emit near the same

Table 2 Primary sources of radioactive liquids

Field	Source	Radioisotope	Properties	Seriousness
Research and development	Nuclear research centers/radioisotopes laboratories	A mixture of radionuclides of short and long terms	• After resin regeneration, batches of neutral pH, uniform • Excellent activity, rich chemicals, small size	• Irradiation instruments • Work and transportation accidents • Internal and external contamination
Research and development	Academic centers	Radioisotopes of short- and long-lived	Fluctuate in volume, activity, and chemical concentration	
Medicine	Radiotherapy	^{14}C, ^{85}Sr, ^{3}H, ^{131}I, ^{32}P, ^{35}S, ^{99}Tcm, ^{125}I	Small size, with chemicals, mainly from patients. The dominated waste is urine, and a smaller quantity of preparation and processing liquids	• Doses from occupational accidents due to excess exposure to radiation in healthcare centers • Irradiation tools • Internal or external contamination
Industry	Production of power	^{3}H, ^{14}C, U (^{233}U, ^{234}U, ^{235}U, ^{238}U) Th (^{232}Th, ^{228}Th)	Large volume, uncertain chemical nature, high activity	• Nuclear power plant accidents • Nuclear proliferation • National security
	Liquids enriched through the mining of rare earth	Ore-type dependent	Big size, uncertain chemical nature, mixed with heavy elements	
	Industrial and pilot plants	Relies on the type of application	Relatively significant volume and has different chemicals	
	Decontamination liquids	Wide diversity	High volume, low activity, and great complexion agents	
	Accidents	^{3}H, ^{90}Sr, ^{131}I, ^{134}Cs, ^{137}Cs, ^{239}Pu	Variable, accident-type dependent	
	Malicious use	Mainly ^{137}Cs radionuclide	Dirty bombs, fatal, contaminated bodies, morgue bodies that contain highly radioactive shell fragment	
	Decommission	^{226}Ra, ^{222}Rn, ^{214}Po, ^{214}Bi, others	Secondary liquids, diversity, have long-lived radionuclides	
	Treatment liquids	^{55}Fe, ^{59}Fe, ^{58}Co	Corrosion products, spent fuel, spent resins, radioisotope production	
Agricultural	Plants and animals	^{134}Cs, ^{137}Cs, ^{90}Sr, U daughters, others	Diverse, organic, non-organic, agricultural-activity dependent	• Irradiation devices • Impacts on biota • Genetic mutation • Environmental changes
Military	Weapon production	Highly enriched with U/Pu, natural U to form UO_2, mixed with U-Pu fuel	Large quantities, the most mobile HLW	• Nuclear emergencies, like a nuclear weapon explosion • Dirty bombs • Transportation accidents involving radiation

radiation levels as those of the Chornobyl disaster, radiation is still a source of ongoing health effects. Therefore, for emergency preparedness and response, this presentation will highlight the scientific literature concerning the manners that deter radioactive liquids from being hazardous, highlighting the latest participation of the academic community in overcoming challenges that affect the decontamination process. Furthermore, this paper compares various decontamination technologies and expectations of the research orientation of radioactive liquid treatment.

2 Treatment Techniques

2.1 Precipitation

Precipitation is a method that removes the particular radioactivity of liquids through the combined precipitating of the precipitant element and the radioisotopes in the liquid, hence matching the target of decontamination (Ahmed et al., 2020; Thakur et al., 2022). The features of this approach are simplicity, lower cost, and a wide range of applications. It was usually used to decontaminate radioactive liquids at the beginning of their formation. Common precipitants are iron, aluminum salts, phosphates, and soda. Generally, radionuclides' carbonate, phosphate, and hydroxide own low or no solubility in the aqueous media. Consequently, they can be removed by precipitation. The parameters that affect the precipitation efficiency are the pH of the mixture, the mixing speed, the mixing time, and the weight of the precipitating element. To promote the coagulation process, clay, activated silica, electrolytes, and other coagulants can be added (Dayarathne et al., 2022). Most precipitating parts struggle to remove a group of radionuclides in the media simultaneously, and some private precipitating elements or other techniques are desired. However, conventional coagulants were utilized for eliminating radionuclides from liquids. Rogers et al. (Rogers et al., 2012) found a novel radioisotope dilution coagulation technique to eliminate cesium radionuclides from radioactive liquid by adding non-radioactive (stable) Cs-133 to the wastewater. Specifically, a rise in cesium stability is utilized to elevate an overall cesium concentration, followed by sodium tetraphenylborate as the coagulant aid to reach the maximum decontamination of Cs-137 from liquid. The test results indicated that the final Cs-137 concentration could be eliminated to the allowable levels of 3.0×10^{-6} Ci/mL, and hence, the US Department of Energy states allowed for liquids to be directly discharged into catchments. Although a coagulation-sedimentation technique is easy and requires a low cost, it encounters obstacles, such as solid-liquid splitting following the treatment process, the significant volume of sludge, and the generation of secondary contaminants that shorten the utilization of this method. Therefore, Luo et al. (Luo et al., 2013) enhanced a co-precipitation microfiltration (PCM) operation to decontaminate Sr^{2+} from liquids. The findings indicated that the decontamination factor and the concentration factor were 577 and 1958, respectively, which overcame the difficulties of solid-liquid separation. Furthermore, Gusa et al. (Gusa et al., 2020) recovered clean liquids and useful salts from water accompanied by extracting oil and gas containing elevated concentrations of Ra-226 and Ra-228 using barium sulfate as a precipitator material. They found that less sludge was produced where the dose of barium sulfate was 25 g/L, the contact time was 30 min, and the saturation index was 4.7. In addition, Oh et al. (Oh et al., 2023) precipitated Cs-137, Sr-90, and Co-60 radionuclides from an acidic liquid produced from chemical treatment of radioactive concrete using potassium Ferro cyanide with $BaSO_4$ as an aiding factor. The optimal parameters were 6-h precipitation time, 0.001 M potassium Ferro cyanide with 0.003 M Fe^{3+} for Cs-137 and Co-60, and $[Ba^{2+}]/[SO_4{}^{2-}] = 0.5$ with $[Ba^{2+}] = 0.06$ M for Sr-90. The results showed that the mentioned radionuclides in the effluent were below the permissible discharge. This process is shown in Fig. 1.

2.2 Adsorption

Applying the adsorption method to decontaminate radioactive liquids usually points to technical utilities for implementing porous adsorbent items to reduce waste radionuclides. Depending on the radioactive liquid characteristic, various adsorbents can be chosen for decontamination. The adsorbent substances can be classified into inorganic materials, such as zeolites, activated carbon, and bentonites; biomass materials, such as cellulose and chitosan; and synthetic polymers materials, such as resins (Attallah et al., 2019; Ma et al., 2020). With respect to inorganic materials, zeolite is inexpensive, available

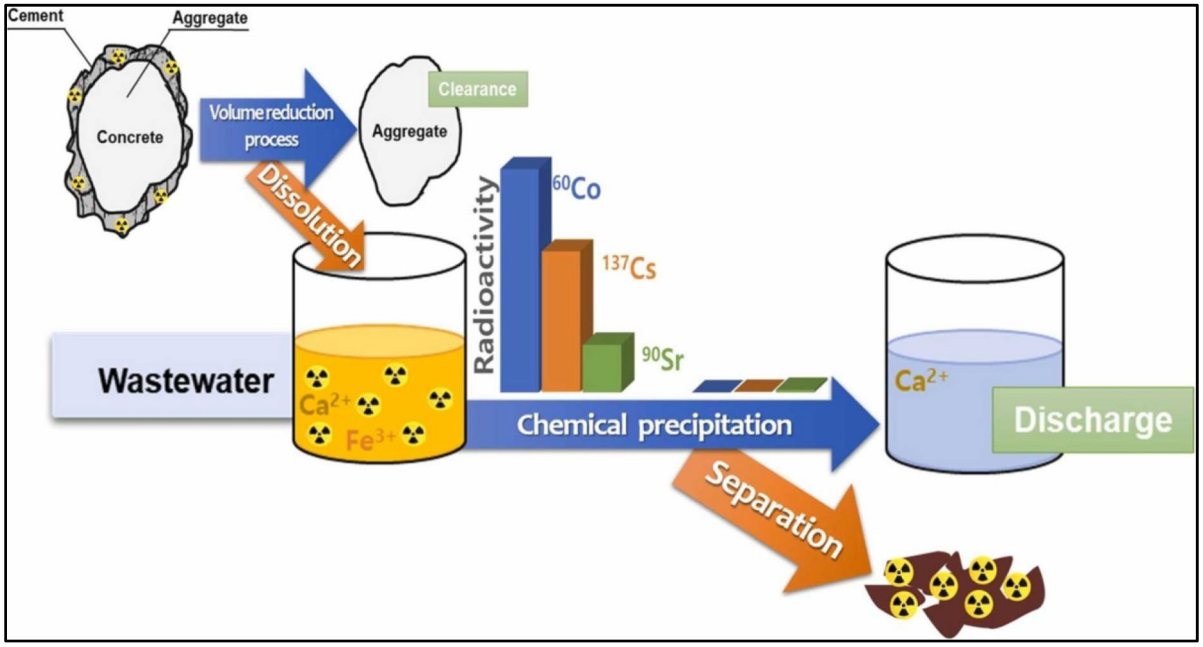

Fig. 1 Precipitation of Cs-137, Sr-90, and Co-60 radionuclides from an acidic liquid using potassium Ferro cyanide with $BaSO_4$ (Oh et al., 2023)

at hand, and has a decontamination factor between sixty-two and sixty-eight. More specifically, it is ten to twenty times more than other adsorbents and works as a filter and an ion exchanger (Gao et al., 2020). Activated carbon exhibits excellent adsorption performance and suitable purification and impurity elimination. However, a low renewal efficiency and an elevated cost restrict its usage. In this regard, it can be noted that raw materials mostly have low adsorption performance. Therefore, the efforts are concentrated on finding adsorbent materials with strong adsorption efficiency and remarkable selectivity. For this reason, Liu et al. (Liu et al., 2022) assembled Fe_3O_4 on amidoxime item MCM-41 to form an adsorbent material called magnetized amidoxime (Fe_3O_4@ MCM-41-PDA/OA) to adsorb U^{+4} and Eu^{+3} from contaminated liquid. They obtained good adsorption capacities of 38.11 mg/g for U^{+4} and 25.36 mg/g for Eu^{+3}. Eka et al. (Eka, 2019) manufactured a polymer from melamine-styrene (MSBP) with good durability against radiation doses, and this polymer was utilized to decontaminate Sr^{2+} ions from the liquid. They showed that the optimal capacity of MSBP for Sr^{2+} is about 142.9 mg/g. On the other hand, Yang et al. (Yang et al., 2020) made sodium-copper ferricyanide functionalized magnetic of nanoscale (NaCuHCF) to decontaminate cesium radionuclides from seawater. They found that the removal percentage of the radioactive cesium with the NaCuHCF-PEI-MNC adsorbent reached 97.35% in the first 5 min, and the highest adsorption performance was 166.67 mg/g. The adsorbent material was very well picked up and had good stability. It can also pick up Cs^+ in participating ions like Na^+, K^+, Mg^{2+}, and Ca^{2+}. Tests with actual seawater revealed excellent removal performance for Cs^+, which was over 99.73% and had a decontamination factor of 372. Al-Nasri et al. (Al-Nasri, 2015) prepared an adsorbent from three kinds of zeolites (clinoptilolite, Y, and A) mixed with carbon-containing diatoms to determine its performance to decontaminate Sr and Co ions from non-radioactive liquid containing salts of the mentioned ions. The gained uptake capacities were 120 mg/g for Co and 290 mg/g for Sr, which were done for a mixing time of 180 min and pH values of 5 and 10 for Co and Sr, respectively. Radhi et al. (Radhi, 2017) studied the performance of (clinoptilolite) zeolite to decontaminate Cs-137 from the liquid resulting from washing soil contaminated

with the nuclide. They found that decontamination efficiency was 90% in mixing time of 2 h. Kim et al. (Kim et al., 2021) synthesized a PB@P-CF complex from a porous carbon foam (P-CF) supported by nanomolecules of Prussian Blue (PB) to adsorb Cs-133 ions from a contaminated liquid. The results gained were a maximum adsorption capacity of 197.7 mg/g and a removal efficiency of 98.8%, achieved at 48 h contact time, 500 g/L adsorbent dose, pH of 7, 300 rpm mixing speed, and at room temperature, as shown in Fig. 2.

Therefore, a wide range of adsorbents were applied to decontaminate radioactive liquids. Nonetheless, the constituents of a radioactive liquid system are complicated, and the efficacy of the adsorbent materials under some extreme circumstances still requires additional studies. To this end, it should be declared that the optimal adsorbents must have much adsorption efficiency, strong selectivity, good stability against extreme conditions, allow regeneration easily, and have a high ability for reuse.

2.3 Ion Exchange

Ion exchange is a method that utilizes the charged particles in the aqueous medium for exchange to realize the objective of removing specific ions. It is generally adequate for decontaminating radioactive liquids with low salinity content (Bashir et al., 2019). In the subsequent handling of radioactive liquids, the low-level radioactive liquids are subject to flocculation and sedimentation processes. Since maximum colloidal particle materials are eliminated in post-pretreatment, the aqueous medium's residual radionuclides are convenient for decontaminating through an ion exchanger. Concerning the kind of substance, ion exchangers could be classified into resin exchangers and inorganic materials exchangers. Recently, the resin exchanger has been given wide consideration. For instance, Nur et al. (Nur et al., 2017) manufactured a resorcinol-formaldehyde polycondensation resin to remove Sr. The results indicated that the exchange capacity for Sr was 2.28 meq/g at a pH value of 7.5–8.5. Moreover, Vasylyeva et al. (Vasylyeva et al., 2021) inspected the decontamination of zirconium, strontium, and yttrium ions using an ion exchanger of resin-type Dowex HCR-s/s material, as indicated in Fig. 3. In particular, the work was performed in batch and continuous conditions. They concluded that the mixing speed and the ion concentrations have a significant effect. The removal of yttrium was less than strontium and less than zirconium from the 10 ng/mL diluted solution.

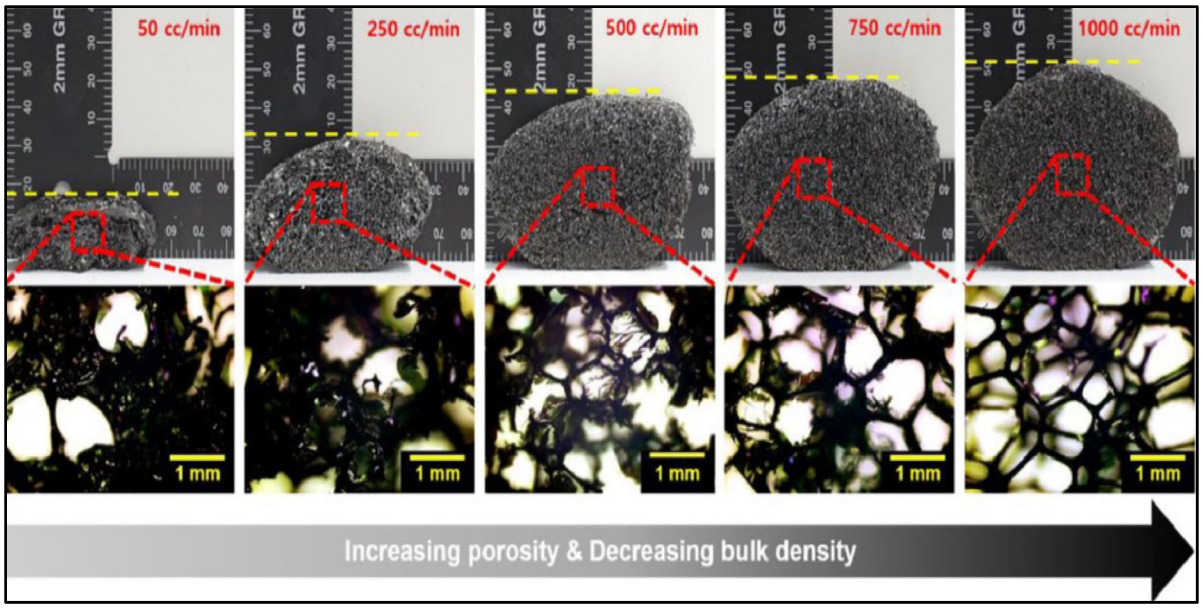

Fig. 2 Adsorption of Cs-133 ions from a contaminated liquid by a PB@P-CF complex (Kim et al., 2021)

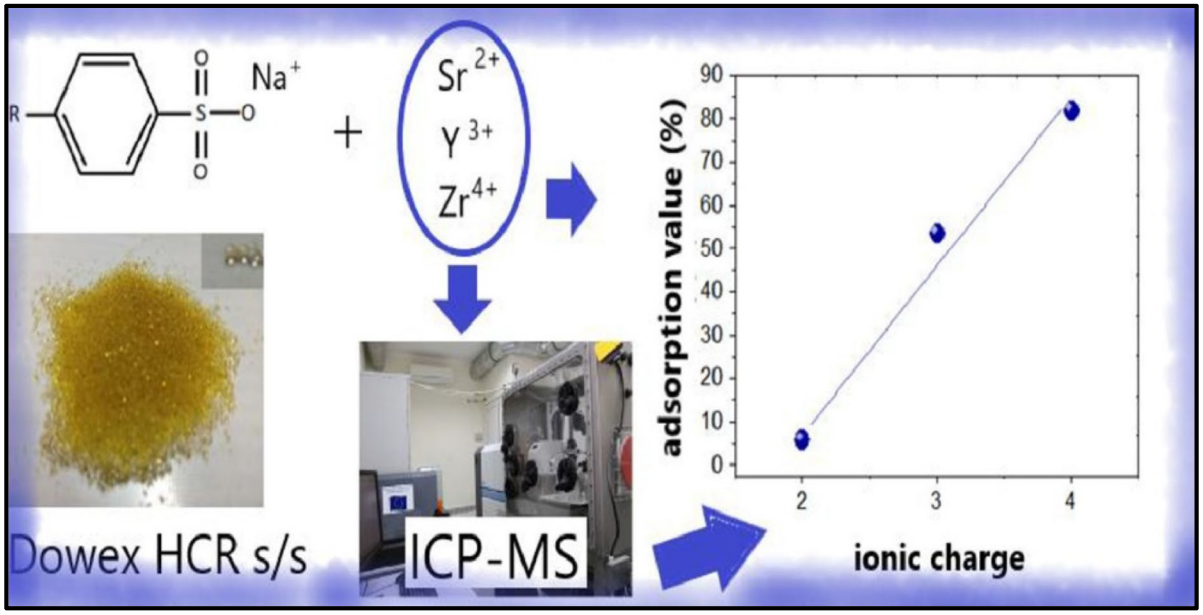

Fig. 3 Decontamination of zirconium, strontium, and yttrium ions using an ion exchanger of resin-type Dowex HCR-s/s (Vasylyeva et al., 2021)

Nevertheless, the encouraged outcomes from using resin ion exchangers have several difficulties, such as low radiation impedance, heat durability, chemical resistance, and high capital costs. Furthermore, the exhausted resin is mostly not reactivated (Figueiredo et al., 2018). In contrast, inorganic ion exchangers are more convenient for decontaminating radioactive liquids due to their chemical persistence and durability against radiation. They have a strong uptake capacity and good pick-up for mono, divalent, and cations. Several types of inorganic ion exchangers involve titanosilicate, hexacyanoferrate metal oxides, zeolite, bentonite or clay, aqueous metal oxides, and others. Conventional adsorbent elements own a lowering adsorption performance, weak selectivity, tiny pore volume, and weak reactivation performance (as organic ion exchange). El-Naggar et al. (El-Naggar et al., 2008) investigated the cesium (Cs^+) adsorption onto fly ash zeolite. The removal efficiency and the exchange capacity were 64.1% and 4.624 meq/g, respectively. In another work, Galambo et al. (Galamboš et al., 2010) implemented montmorillonite and bentonite as adsorbents to remove Cs-137 from radioactive liquid, and the great capacity was 0.88 mmol of Cs-137/g. In comparison, raw inorganic elements' adsorption or ion exchange efficiency was relatively depressed. Therefore, natural inorganic substances obey modification for radioactive liquid decontamination. Nilchi et al. (Nilchi et al., 2012) prepared and used a composite material of manganese dioxide-polyacrylonitrile (MnO_2-PAN) to reduce Cs-137. The adsorption capacity of the composite material was 2.42 mmol/g. To enhance the pick-up of cesium, Han et al. (Han et al., 2018) utilized low-pressure suction vaporization to merge the sulfur with the zeolite. However, incorporating sulfur did not give additional active sites for adsorption, which donated the electronic section to the zeolite part. Ions raise the capacity of the ion exchanger to pick up Cs^+ by supporting more correlations. Modern research works have revealed that modification of metals, such as nanocomposites with structures of organic elements, makes them have significant porosity, a high surface area, and a robust system, and makes them easily applicable in decontaminating radioactive liquids. Yousefi et al. (Yousefi et al., 2015) designed a cobalt hexacyanoferrate (CoHCNF)@polyaniline nanocomposite utilizing the secondary precipitation technique. The resulting capacity for Cs^+ adsorption at 20 °C was 92.12 mg/g. In addition, Yang et al. (Yang, et al., 2017) constructed nanoparticles of sodium hexacyanoferrate (NaCuHCF) to remove Cs^+

radionuclides from seawater. At 5-min contact time, they reached Cs^+ removal efficiency and adsorption capacity of 97.35% and 166.67 mg/g, respectively. On the other hand, pure organic substances have economic characteristics with lower cost, stable and durable properties, and they are modifiable. They can be utilized as biosorbents. Genevois et al. (Genevois et al., 2017) mixed forestry waste with 2, 2.6, 6-tetramethylpiperidine-1-oxyl radical (TEMPO) and nickel hexacyanoferrate (NiHCF) to adsorb Cs^+ from wastewater. The obtained adsorption capacity was 1.51 mmol/g. Pangeni et al. (Pangeni et al., 2014) prepared biosorbent from persimmon waste, which showed perfect adsorption capacity for Cs^+, which reached 0.76 mmol/g. In this regard, it can be noticed that the sorption process has great performance in decontaminating radioactive liquids. In addition, it is worth mentioning that sorption materials have high adsorption capacity, must have great stability, and are easily activated and reused.

2.4 Membrane Separation

The membranes are functional materials with high selectivity for separation, and their selectivity may perform separation, decontamination, concentration, and other processes (Gul et al., 2021). Membranes can be grouped according to the separation mechanism, the type of membrane material, and the membrane driving force. Based on the controlled driving force, the membrane can be categorized into a pressure-driven, a concentration-gradient-driven, an electrical–potential-driven process, and a temperature-driven membrane separation (Tofighy & Mohammadi, 2020). For the pore size, the membranes are divided into several types, such as reverse osmosis, ultrafiltration, nanofiltration, and microfiltration. They have several positive aspects, such as power-saving, environmental rehabilitation, high performance, low cost, and ease of control. They are widely applicable in food manufacturing, hydrometallurgy separation, energy recovery, sewage treatment, etc. Their particular composition and high-performance rejection make them widely suitable for water treatment (Al-Ani et al., 2021). In the first stage, they were used for seawater desalination and pure water production. With the evolving technology, they have recently been widely implemented in decontaminating radioactive liquids. The membrane operation used for decontaminating radioactive liquids has the features of highperformance, a big concentration size, energy-saving, an uncomplicated system, flexible functionality, and easy installation. It can be chosen in line with the synthesis of the radioactive liquids, the situation of the mixture, and the membrane type (Korolkov et al., 2019; Rashida et al., 2020a).

Microfiltration (MF) membranes retain big molecules or macromolecules with a size of 0.1–1 µm. In the nuclear field, these membranes are often used for pretreatment or screening the large particles generated in the condensed liquid after settlement. Under pressure variation, molecules with a size more significant than the hole size of the membrane are retained to obtain a separation result. The significant pore volume mostly reduces suspended particles in liquids and other big molecules. It cannot immediately and effectively eliminate the radionuclides in the liquids. It is generally required to be used as a group with other operations. Zhao et al. (Zhao, 2007) decontaminated the low-level liquids contaminated with plutonium using flocculation, sedimentation, and microfiltration. They added a suitable weight of ferrous sulfate and adjusted the radioactive liquid's pH. They achieved a plutonium removal efficiency higher than 99.9%. Furthermore, the mixed liquid comprising uranium, americium, and plutonium was handled through the merged process of flocculation and microfiltration, and a single-stage gross Alpha removal efficiency of 99.87% was reached. Ceramic filters can gain an elevated decontamination factor and a great concentration coefficient for decontaminating high-level radioactive liquids. The pore diameter of ultrafiltration membranes (UF) is mostly 0.001–0.1 µm. Generally, only soluble elements will pass while the agglomerated and suspended particles are screened. In the developed treatment, ultrafiltration mostly removes colloids and suspended particles in the liquids. In particular, ultrafiltration can be employed for the pretreatment phase preceding the reverse osmosis phase and it can be a group with adsorption, precipitation, or complexation processes. Zhang et al. (Zhang et al., 2017) searched the impact of low-activity positive surfactants on the removal performance of mineral ions in the ultrafiltration technique. They found that when the quantity of CTAB (hexadecyl trimethyl ammonium bromide) is decreased below the critical concentration, the removal efficiency of Cs^+ radionuclides rises from 24–33% to 50%. Moreover, Sr^{2+}, Co^{2+}, and

Ag^+ removal efficiencies are raised to greater than 90%. The pore volume of nanofiltration membranes is mostly 1–2 nm, and their generality is electrically charged composite membranes. They are functional semipermeable membranes that allow some molecules with low molecular weight, ions with low-valet, or solvent molecules to pass through. The retention performance of ions with multivalent is greater than that of ions of monovalent (Chen et al., 2018). Lu et al. (Lu et al., 2016b) synthesized a TiO_2-doped ZrO_2 nanofiltration membrane. They applied it to decontaminate simulated radioactive liquid, reaching a rejection efficiency of 99.6%, 99.2%, and 75.5% for Co^{2+}, Sr^{2+}, and Cs^+, respectively, showing that the nanofiltration membrane is efficient for Co^{2+} and Sr^{2+} and it has a high removal efficiency. Reverse osmosis is a technique in which the driving force is a differential pressure to extract the solvent from the mixture (Rashida et al., 2020b). It can pick up different metal ions from the mixture well, has a good activity and purity impact on the combination, and is extensively used to decontaminate radioactive liquids. Gu et al. (Gu et al., 2015) operated a two-stage reverse osmosis system to study the decontamination of boron from the radioactively contaminated liquid. They found that the gross salt removal efficiency was more than 99.50%, and the gross boron removal efficiency was more than 84.30%, which has a good impact on both Cs-137 and Sr-90 in the liquid. The removal impact demonstrates that the reverse osmosis technique has a high purification impact on the radioactive liquids. Additionally, electro-dialysis, the distillation of membranes, supported liquid membranes, etc., have been deeply searched in the scope of radio-chemical separation (Jia et al., 2017). Alsarayreh et al. (Alsarayreh et al., 2022) prepared zeolite-type NaY modified by membranes of polyethersulfone to decontaminate Cs-137 from a radioactive liquid of pH 7.5. They achieved over 90% Cs elimination, and the DF was 10.2. However, when they added copper Ferro cyanides to the solution, the elimination efficiency for Cs reached 99.2%, and the DF increased to 121.2, as indicated in Fig. 4. Compared with other membrane separation operations, osmosis membranes have a great removal rate of cesium ions. The membrane type CTA (cellulose

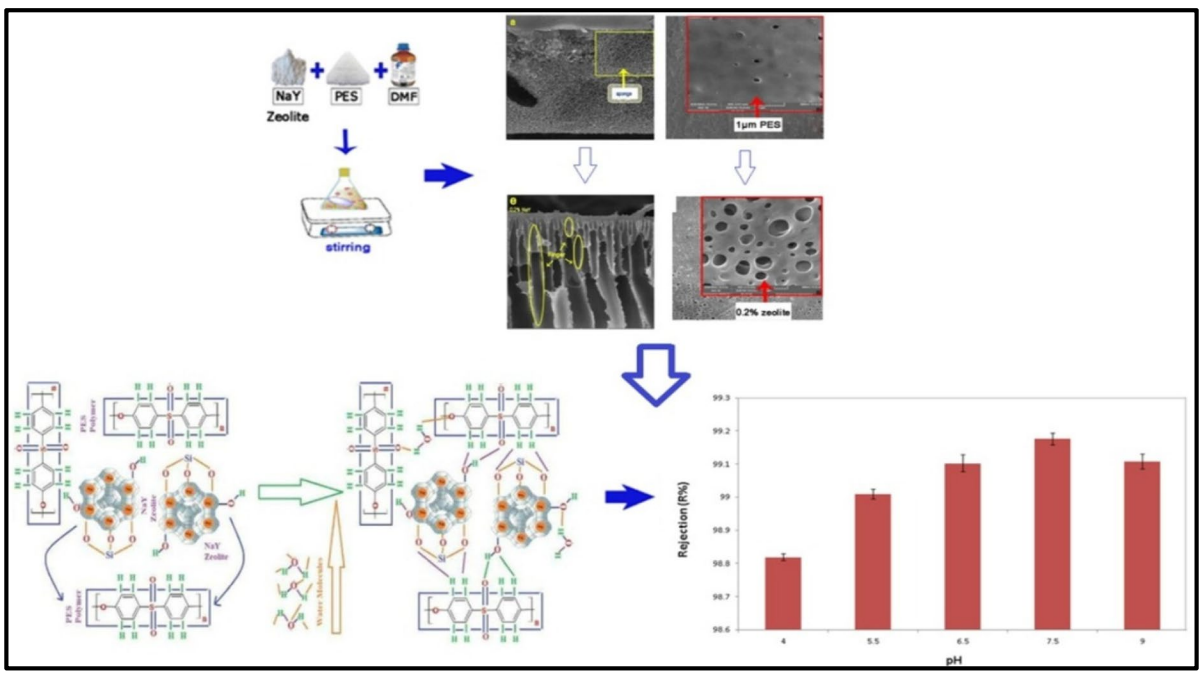

Fig. 4 Membranes of polyethersulfone-modified zeolite type NaY to decontaminate Cs-137 from a radioactive liquid of pH 7.5 (Alsarayreh et al., 2022)

triacetate) introduced a great retention efficiency of 90.35–97.15% for cesium ions. Zdorovets et al. (Zdorovets et al., 2020) used contact membrane distillation to treat liquid radioactive waste (DCMD) using polyethene terephthalate (PET) to estimate the decontamination factor and the rejection degree. The results revealed that Co-60, Cs-137, and Am-241 decontamination factors were found to be 85, 1900, and 5, respectively. The contrast with the rejection degree was mostly more than 90% and close to 100% for radionuclides Na, Mg, Sr, Fe, Al, Ca, Sb, K, Mo, and Cs ions.

In this context, the membrane separation method has several features. In particular, it provides high performance. Furthermore, some separation methods are eco-friendly and provide exceedingly environmental preservation. In contrast, this method has some problems, such as membrane fouling, which is a great challenge for keeping the membrane flux and decreasing repeated maintenance. In addition to the unique characteristics of radioactive liquids, high-level radioactivity exposures will automatically damage the membrane structure, leading to lower membrane efficiency and a decreasing virtual life (Deng et al., 2020). Consequently, the durability of the materials used in membranes to resist harsh environments must be discovered. The membrane structure is damaged under high-level radioactivity, leading to bad efficiency and decreased life. To achieve control of the primary obstacles and guide the best development of radioactive liquids decontamination, certain steps could be considered, such as optimizing the operation conditions, enhancing the procedure, and decreasing the mixing time, in addition to focusing on the research and development of how to prevent or reduce membrane fouling (Alsalhy et al., 2018). Additionally, in real radioactive liquids decontamination, the membrane methods are restricted by the demand for fast removal of radionuclides. In the subsequent stage of solid-liquid separation systems, microfiltration and ultrafiltration might be grouped with adsorption, precipitation, flocculation, and other techniques. Although nanofiltration and reverse osmoses can immediately retain radionuclides in liquids, a pretreatment operation must match the water quality standards. For example, several water stations in Canada and the USA have attempted stratifying membrane methods for actual radioactive liquid decontamination. However, it is still vital to improve and develop raw membrane materials and membrane methods to decontaminate radioactive liquids to raise the performance of this technology.

2.5 Vaporization Concentration

For decontaminating and disposing of radioactive liquids, vaporization is usually used for concentrating such liquids. The initial working base is to subject the radioactive liquids to the evaporator and heat them by an electrical heater or through hot steam. The continued heating makes the radioactive liquid evaporate and form water vapor. Then, it is cooled through condensation systems to produce condensed water. After that, it is reused or recycled, while the stable radionuclides in the sludge are concentrated and then obey the solidification process (Deng et al., 2020). The concentration of radioactive liquids through vaporization is an assured technique that can notably eliminate the quantity of radioactive liquids (Tashlykov et al., 2021). This process is widely applied in decontaminating radioactive liquids, especially with waste having relatively high activities and surely with volatile radioisotopes. It has a decontamination coefficient and features a high-volume minimization effect, considerable flexibility, a broad range of applications, and the ability to combine with different technologies. This technique does not demand additives and will not generate secondary wastes (Wu et al., 2023). To enhance vaporization performance and reduce tool working costs, specialists have exerted efforts in the expansion to find new evaporators, and they have obtained noteworthy results in developing different evaporators. Based on the efficiency comparison between an evaporator of external heat and an evaporator of kettle type, Hu (Hu, 2018) suggested implementing a kettle-type evaporator to decontaminate the high activity level liquids generated through the spent fuel handling facility. It has individual features in decontaminating acidic radioactive liquids, such as investigating the "continuous vaporization-de-nitration" operation. By targeting some of the generated gas in the de-nitration operation, the structure of the kettle evaporator unit can also treat the foaming arising during de-nitration and decrease the radioactivity level of the condensate liquid. As the output ability is affected by the restricted heat exchange zone, dimensions have also been suggested to suitability increase the inner heating interchange pipes and mixing tool to raise and enhance the

size and the efficiency of the heat exchange. Evaporators of natural circulation-type, rising film type, and kettle-type are exceedingly applied in the conventional vaporization and concentration method of radioactive liquids. However, the direct heating technique for the use time will lead to the exhaustion of a significant quantity of major electricity or steam, consuming a great power. Similarly, the exhaustion of condensate is also considerable. Compared with conventional vaporization, the mechanical steam re-compression (MSR) method achieves energy rescue based on the philosophy of a heat pump. A condensate deals with the preheating for the untreated liquid, reducing the further condensate feeding (Xia, 2019). Xu et al. (Xu et al., 2016) utilized a group of MVR type 50 L/h vaporization instruments to conduct an artificial wastewater vaporization test that involved cobalt, strontium, and cesium radionuclides. The results indicated that the instrument purification factor was greater than 7×10^5, and the percentage of saving energy was above 88.7%, compared with the conventional evaporator, which confirmed that the MVR instrument has high performance in the decontamination of radioactive liquids. Wei (Wei, 2009) improved a vaporization and condensation tool that works by vacuum to decontaminate radioactive liquids produced from military activities. He used vacuum distillation to remove radioactive impurities, which is a process of lowering the boiling degree using a system under vacuum pressure. The thermal experimental results revealed that the gross Alpha and Beta decontamination factors for the radioactively contaminated liquid were 3.14×10^4 and 2.49×10^4, respectively, and the gross Alpha and Beta decontamination factors for the intermediate-level liquid were 4.37×10^4 and 2.04×10^6, respectively. The device worked stably, and the quality of the treated liquids matches the requirements and meets the related disposal criteria. Besides heat-industrial sources, solar energy is also broadly considered a heating source. For example, Karen et al. (Karen et al., 2023) carbonized and coated sawdust with cotton in various weight ratios as an outdoor solar absorber to desalinate from the liquid of 120 ppm and neutral pH, in series having different doses of the solar absorber. The optimal weight ratio was 60% from the solar absorber, conducted within 2 h, which achieved 63% removal at a vaporization rate of 1.15 kg/m^2 h, as indicated in Fig. 5. Under a single sun's rays subjection, the solar evaporator has good absorption of light and heat, is heatproof, and has rapid liquid transporter properties (Abid et al., 2017). Hence, it matches a quick vaporization performance (1.60 kg/m^2 h) and a great amount

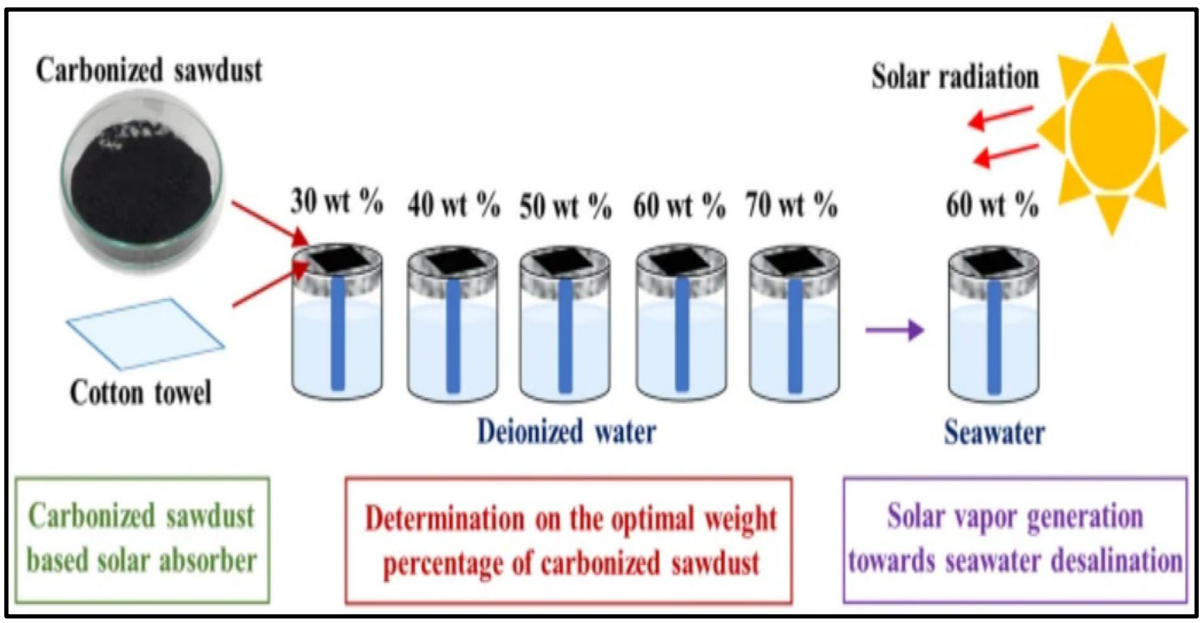

Fig. 5 Solar absorber radioactive liquid treatment (Karen et al., 2023)

of interfacial water vaporization rate (92%). In this regard, solar-driven interface vaporization could be efficient in decontaminating radioactive liquids.

An infrared heater has several applications. It works because liquid molecules have significant infrared absorption efficiency (Hashimoto et al., 2019). Xu et al. (Xu, 1992) reached a purification factor of 10^4 by heating of radioactive liquid through infrared rays. This manner evaporates the surface of water with no foaming and boiling compared to conventional vaporization. The removal efficiency is excellent, and the instruments are unharmed, powerful, easy to work and operate, relatively rust-resistant, and economical. It is a system that generates low secondary waste. The vaporization manner technology is somewhat ripe and appropriate for decontaminating liquids of small amounts and high activity. Generally, a significant percentage of radionuclides in liquids are not volatile. The radioactive liquid can be vaporized and intensified to steam the liquid in the mixture into vapor slowly. After that, it cools down to produce condensed water. Many radionuclides remain in the concentrated residual, then they are solidified and encapsulated to achieve a high DF. However, the vaporization manner has restrictions for eliminating volatile radionuclides in liquid. For instance, iodide in radioactive liquids is highly volatilized. Hence, the decontamination of liquid involving iodine radionuclides is inadequate for vaporization. The vaporization technique has the following disadvantages: it is energy-depleting, has little heat-producing, and requires a high cost; it is insufficient to handle liquids that quickly generate foam and involve volatile radionuclides; when treating acidic liquids of high-level radioactivity, the boiling degree rises, the performance declines, and more instruments encounter corrosion as the acidity elevates; furthermore, the manifestation of fouling, burst, etc., must also be taken during the design stage (Wang et al., 2018). Therefore, extra expansion of novel high-performance evaporators and investigation of modern vaporization methods are indispensable for future work.

2.6 Biotechnology

Biotechnology decontaminates radionuclides through bioconversion, biosorption, biomagnification, deposition, and solubilization using green plants or microorganisms as media (Nivetha et al., 2022). This method has the features of eco-friendly, strong efficiency, mildness, economic, energy saving, and few secondary wastes. It highly eliminates radioactive waste (Vanhoudt et al., 2018). Biotechnology has been searched for decontaminating low-level radioactivity liquids since the 1960s, and rapid evolution has happened until now. For instance, Ferreira et al. (de Pádua Ferreira et al., 2012) propagated a colony of bacteria in the zone of uranium mining and in another site of no uranium mining to decontaminate radioactive liquid. They found that the colonies reproduced in the location containing uranium had higher radioactive organic liquid digestion and radionuclide sorption than the colony propagated in the zone of free uranium. The colonies reproduced in the uranium soil may adsorb 92% of natural uranium and 100% of Am-241 and Cs-137 at higher radioactivity intensities. The mentioned study results showed that the colonies propagated in the ground of the uranium mining zone are adequate for handling a big quantity of radioactive organic liquid. Gorbunova et al. (Gorbunova et al., 2015) applied microbial colonies as the primary treatment of radioactive organic liquid. The outcomes indicated that because of the functional elements on the biosurface, the microbial colony could oxidize 60% of the organic substances into H_2O and CO_2, which can firmly eliminate the quantity of the radioactive liquid. The method of taming microorganisms to decontaminate radioactive liquids is comparatively tricky and is highly affected by factors such as pH, radionuclide type, processing time, and radioactivity level. Liu et al. (Liu et al., 2015) proposed a type of bacteria called *Bacillus subtilis* to decontaminate Sr^{2+} from radioactive liquid. They studied the effect of the pH degree, the liquid temperature, and the intensity of the initial ion on the adsorption removal. It was discovered that at a pH degree of 6.3, room temperature, concentration of 15 mg/L, and mixing time of 24 h, the decontamination rate was 96.3%. Various biosorbents have broadly studied the biosorption of isotopes, such as Sr, Cs, Th, and U (Gorbunova et al., 2015). Ji et al. (Ji et al., 2019) removed 99% of Tc-99 radionuclides from simulated groundwater by carboxymethyl cellulose (CMC) supported by nanoparticles of zero valiant iron (nZVI), as illustrated in Fig. 6.

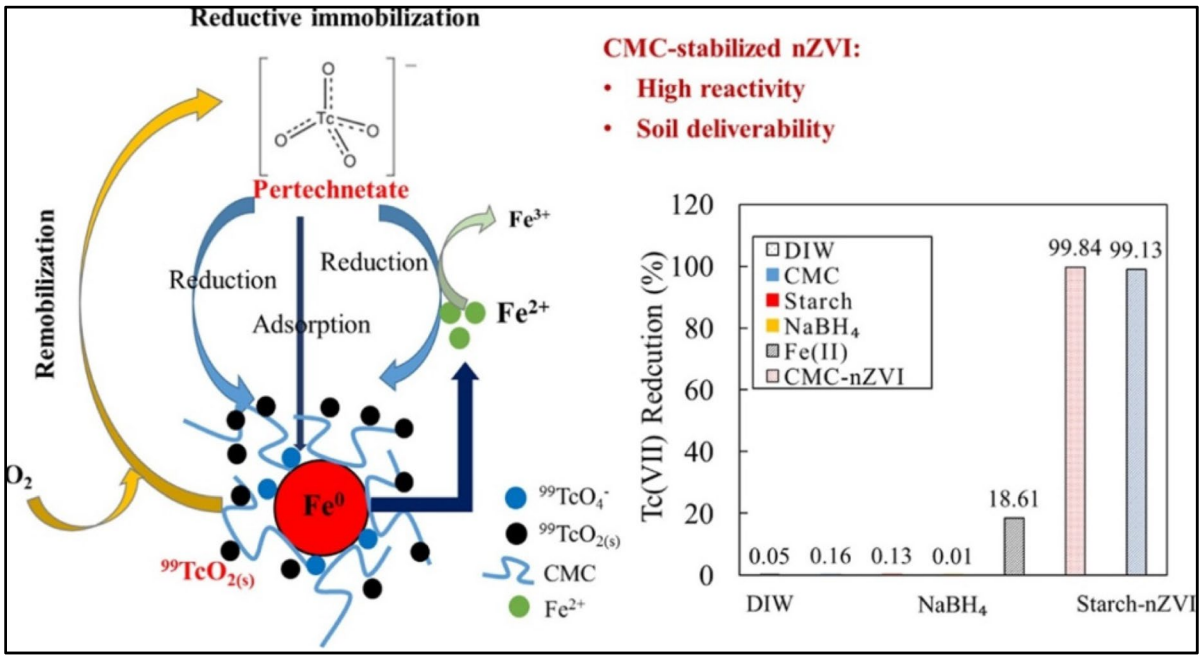

Fig. 6 The reduction of Tc-99 by nZVI material (Ji et al., 2019)

2.7 Photo-catalysis

Photo-catalysis means converting renewable or solar power into chemical power in the existence of light as a catalyst aid (Li et al., 2021). In this manner, the photo-catalyst can alter the chemical bonds for the reactants after soaking up the light. The moved photo-catalyst can react with the reactant materials several times. Intermediate items are generated, including those that stay stable before and after the motivation (Bogaerts et al., 2023). As indicated in Fig. 7, when the motive quantum energy of light is of the same magnitude or exceeds the semiconductors' prohibited bandwidth, the band of valence electrons are agitated to move to the band of conduction, producing gaps between the band of valence and the

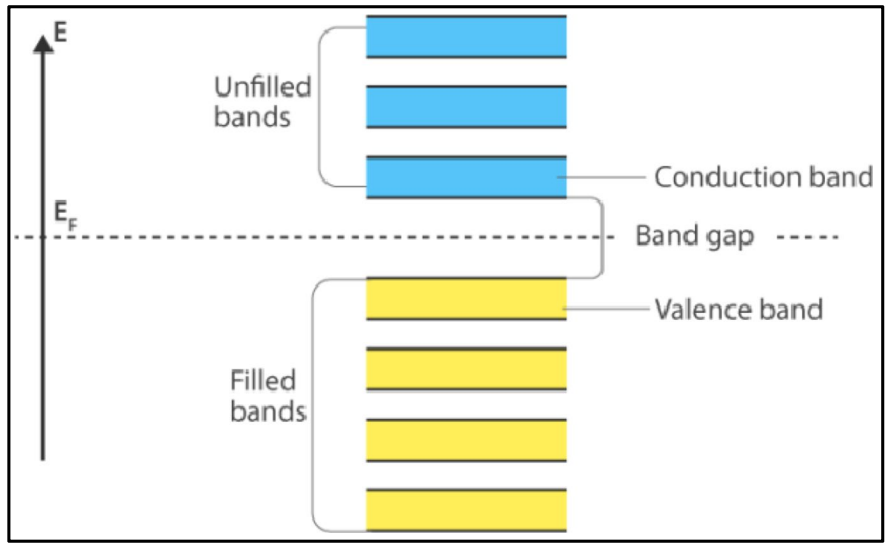

Fig. 7 Valence band and conduction band (Tahir et al., 2021)

band of conduction (Nunez et al., 2019). They generate photo-produced electrons in the conduction band. The photo-produced electrons generated on the band of conduction have decreased credible energy, while the photo-produced gaps on the valence band consume solid energy. They may escape to a semiconductor roof and are subject to symmetric oxidation-reduction interactions with the adsorbed pollutants on the roof material (Gao, 2022). In radioactive liquids, organic liquids and liquids contaminated with tritium are two exceptional liquids. They cannot be treated through concentration, membrane, vaporization, and ion exchange and they need careful management. They involve radioactive oily wastes, carbon-based solvents, carbon-based scintillation fluid wastes, and secondary wastes. The photo-catalytic decontamination method could be a reference in decontaminating organic liquids (Thiruramanathan et al., 2023). The formed photo-produced electrons are mostly moved to a roof of a semiconductor via transformation gaps and electrons in the subsequent formations. By integrating the electron with gaps at a weak point in a semiconductor, the reintegrated electron and electrons of contaminants that were adsorbed on the surface of the semiconductor encounter the reduction process. Gaps are moved to the outside, where the oxidation process takes place with the element donor (Tahir et al., 2021).

In the photo-catalysis operation, it is necessary to speed up the segregation between the electron and the gap, decrease the amount of electron-hole reintegration, and enhance the photo-catalysis performance (Ghime & Ghosh, 2020). For instance, the widespread element is uranium (U). It may be as U^{6+}, U^{5+}, U^{4+}, and U^{3+}. The two stable forms in the environment are U^{4+} and U^{6+}. U^{6+} is hydrophilic, with elevated toxicity and rapid transition in the media. U^{4+} has low toxicity and is hydrophobic. Therefore, transforming U^{6+} to U^{4+} is a flagship way to remove and retrieve U from liquids (Lussier et al., 2016). Wang et al. (Wang et al., 2015) discovered that sodium formate is able to raise the performance of U^{6+} to ascend the TiO_2 surface. In sodium formate, the adsorption capacity of U^{6+} is elevated to 44 mg/g. The photo-catalytic elimination rate raised to 17-fold. Lu et al. (Lu et al., 2016a) prepared boron-doped g-C3N4 in different ratios. Among these ratios, 1.0% weight of boron-doped doping gives the best impact, where it could fully decontaminate a volume of 200 mL with 0.12 mM U^{6+} in the first 20 min. Additionally, the series performance of five loops was higher than 90%. Guo et al. (Guo et al., 2016) manufactured a zinc oxide and retorite mixture substance in a sol-agel manner using methanol, which is an organic item, to improve the adsorption efficiency and photo-catalytic elimination concentration of U^{6+} on zinc oxide/retorite complex material. In addition, the combined substance indicates substantial light concentration reduction after four series of reactions within visible light exposure. In the studying field of photo-catalytic decontamination of uranium, several kinds of photo-catalysts exist involving TiO_2 and its associated composites (Wang et al., 2015), iron oxide and its compounds (Li et al., 2017), g-C3N4 and its composites (Jiang et al., 2018), and supplementary photo-catalytic substances. Nevertheless, most photo-catalytic items have low decontamination performance and lower absorption efficiency of sunlight, which allows to implement photo-catalysts in decontaminating liquids involving natural uranium. Consequently, building up a novel visual light catalytic elimination method is a significant investigation trend for the photo-catalytic decontamination of liquids comprising uranium.

3 Conclusion

Since radionuclides are highly hazardous to health and the environment, plenty of scientific publications concentrated on removing them from real or simulated radioactive liquids. From the above discussion, we conclude that each method has its properties and restrictions. More specifically, the precipitation method is comparatively unsophisticated, cost-saving, and widely applicable. Despite this, it usually has bad selectivity and forms large secondary wastes. Ion exchange is a method to remove certain particular ions in radioactive liquids with low salinity content. Adsorption processes have a wide range of applications to decontaminate radioactive liquids. Despite this, the constituents of the radioactive liquids system are complicated. The membrane method demands high-quality influent. However, due to prolonged usage, equipment tends to close, leading to high repair and maintenance costs. Biotechnology is also applied to remove radioisotopes. In contrast, high radiation causes the death of microorganisms. Overall, photo-catalysis is considered a modern world for decontaminating radioactive residues. It can be a reference in processing organic liquids compared to other fields, particularly macromolecular organic

spent liquids. In addition, an efficient integrated treatment system can be generated by merging two or more decontamination methods to achieve high removal performance for radioactive elements from contaminated liquids. It is worth mentioning that integrated treatment systems have a vital function in the advanced treatment of depleted fuel, principally exploited to decrease the amount of radioactive liquids.

Data Availability Not applicable

Declarations

Conflict of Interest The authors declare no competing interests.

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