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Research Paper

Current status and prospects of research on 1,4-dioxane pollution and treatment technologies in the water environment

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Abstract: 1,4-dioxane pollution is characterized by its early identification, widespread sources and extensive distribution. The pollutant is highly mobile and persistent in the water environment and is classified as a B2 (probable) human carcinogen. After reviewing recent researches on the pollution status, transport and transformation characteristics of 1,4-dioxane in the water environment, as well as the environmental pollution remediation and treatment technologies, and the status of environmental regulation, this paper addresses that the distribution of 1,4-dioxane in water bodies is significantly correlated with chlorinated hydrocarbon pollutants such as 1,1,1-trichloroethane (1,1,1-TCA) and trichloroethylene (TCE). It is noteworthy that 1,4-dioxane often occurs in symbiosis with 1,1,1-TCA and has a similarity contamination plume distribution to 1,1,1-TCA. The natural attenuation of 1,4-dioxane in groundwater environment is weak, but there is a certain degree of biological oxidation attenuation. Current methods for treating 1,4-dioxane pollution mainly include extraction-treatment technology, advanced oxidation treatment technology, modified biological treatment technology and phytoremediation technology, all of which have their limitations in practical application. Currently, there is no environmental regulation available for the 1,4-dioxane pollution worldwide, and no enforceable standard established for defining the health trigger levels of 1,4-dioxane in drinking water. Research on this contaminant in China is generally limited to the site or laboratory scale, and there are no studies on the environmental risk and quality standards for 1,4-dioxane in the water environment.

Keywords: 1,4-dioxane; Chlorinated hydrocarbon; Environmental pollution; Attenuation

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Introduction

1,4-dioxane is a cyclic organic compound that can pose a serious hazard to humans. When inhaled as a vapor, it can irritate the respiratory tract, mucous membranes, and central nervous system, damage human skin, kidneys and liver, and may even cause

death in acute poisoning (ATSDR, 2012; IARC, 1987; Stickney et al. 2003; Ernstgård et al. 2006; US EPA, 2013; US EPA, 2018c).

1,4-dioxane was introduced as a synthetic industrial chemical in 1863 and has been used commercially as an industrially important substance since 1929 (Mohr, 2010). Due to its significant solubility and stability, 1,4-dioxane is widely used as a solvent, wetting agent, dispersant, and aerosol additive, and has historically been used in large quantities as a stabilizer for chlorinated solvents, particularly for 1,1,1-TCA. 1,4-dioxane has also been used in the preparation of tissue sections (US EPA, 1995; Mohr, 2001; Zenker et al. 2003) and has been found in a variety of industrial products such as insecticides, fumigants, aircraft de-icing agents, and antifreeze. In addition, 1,4-

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dioxane occurs as a by-product in the manufacturing process of certain surfactants (e.g. polysorbate, sorbitol, and sorbitol loss) and in the wastewater of polyester production facilities (Reierson, 1995; Shen et al. 2017; Dawson et al. 2022).

This wide range of applications makes it a widely available environmental pollutant. US EPA data shows that solvent use alone released approximately 617 000 pounds of 1,4-dioxane in 2017 (US EPA, 2017a; US EPA, 2018b). According to the European Chemicals Agency, the EU produces and/or imports ≥ 1 000 tons of 1,4-dioxane per annum (ECHA, 2021). Sources of 1,4-dioxane contamination are primarily a number of industrial sites, including sites where chlorinated solvents are used and stored, landfills, and industrial facilities that produce, process, or use 1,4-dioxane, and are particularly extensive in soil and water environments affected by chlorinated solvents (Anderson et al. 2012; Adamson et al. 2014; Adamson et al. 2015; Adamson et al. 2016).

Developed countries in Europe and the United States have been concerned about 1,4-dioxane pollution for a long time. As early as the 1990s, US EPA and the International Agency for Research on Cancer classified it as a B2 (probable) human carcinogen (IARC, 1999). China began to pay attention to this problem in 2009–2010, when 1,4-dioxane was detected in a Chinese shampoo brand and sparked strong public concern. In recent years, China has been paying more and more attention to environmental protection and ecological civilization construction, and will also make great efforts to eliminate non-mainstream pollutants including 1,4-dioxane. Therefore, understanding the current research on 1,4-dioxane in water environment pollution and recognizing the characteristics of its pollution in the water environment can help promote the concern of this issue in China. Therefore, we need to understand current status of research on the water environment pollution due to 1,4-dioxane migration and recognize the characteristics of its pollution behavior in the water environment, which will help promote the attention and scientific concerns of this issue in China.

1 1,4-Dioxane water environmental pollution status

1,4-dioxane was identified as an significant contaminant in the water environment about 5 decades ago and was widely distributed. As early as the 1970s, US scientists discovered the presence of 1,4-

dioxane in water (Kraybill, 1978; Burmaster, 1982). Subsequently, it has been found in an increasing number of locations, including Japan (Abe, 1999; Tanabe et al. 2006), Korea (An et al. 2014), Canada (Health Canada, 2018), the United Kingdom, and Germany (Stepien et al. 2013; Stepien et al. 2014; Karges et al. 2018). US EPA reported that 1,4-dioxane was detected in approximately 19% of public water systems as of December 2013 (US EPA, 2013); the third round of unregulated contaminant monitoring rules conducted in the United States from January 2013 to December 2015 showed that 1,4-dioxane was detected in 21% of samples from 4 864 public water systems and 6.9% exceeded the health reference concentration (0.35 $\mu\text{g/L}$) (Adamson et al. 2017). In Europe, pollution in relation to 1,4-dioxane has been discovered in surface water and groundwater in Germany, the Netherlands and the UK (Stepien et al. 2014; Chiang et al. 2016; Karges et al. 2018), as well as been detected in the leachate from Swedish municipal landfills and in the industrial wastewater from polyester resin producers (Romero et al. 1998; Paxe'us, 2000). The content of 1,4-dioxane has been tested in several drinking water production sites in the Netherlands (Ministry of Environment and Infrastructure, Netherlands, 2015). The contamination of 1,4-dioxane has received extensive attention in Japan since it has been identified at various water bodies as landfill leachate (Yasuhara et al. 2003; Fujiwara et al. 2008), wastewater from sewage treatment plants (Abe, 1999; Tanabe et al. 2006), rivers, offshore seawater, and groundwater (Abe, 1999; Huang et al. 2001; Kawata et al. 2003). In addition, 1,4-dioxane has been detected in groundwater in the Arctic (Alaska) (Lesage et al. 1990; Adamson et al. 2015). In China, the contents of 1,4-dioxane in detergents such as hand soap, face wash, and bath soap have been reported. However, the distribution of the 1,4-dioxane in natural water system has not been comprehensively studied, and the environmental pollution status of 1,4-dioxane is yet not known (Ma et al. 2015).

2 Environmental behavior of 1,4-dioxane in water

1,4-dioxane has two symmetrical ether bonds (Fig. 1), and this chemical structure makes it highly hydrophilic, stable and not easily adsorbed. Meanwhile, it is not easy to be hydrolyzed or photolyzed in the environment because there are no easily hydrolyzed groups in its molecular

structure and it does not absorb natural light. Its characteristics above determine that it is difficult to be adsorbed in soil after entering the natural environment and will be rapidly transferred to water environment. Therefore, 1,4-dioxane is more likely to pollute the air and water than the soil (Sei et al. 2010).

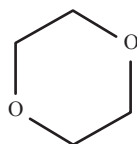


Fig. 1 Molecular structure of 1,4-dioxane

Studies have also shown that 1,4-dioxane is not easily volatile in water environment, not easily adsorbed by activated carbon, not easily oxidized by common oxidizers, not easily biodegradable, and highly migratory and persistent. These characteristics make it more likely to contaminate surface and groundwater, and more likely to spread, and also difficult to remove from the natural environment (Alexander, 1973; Alexander, 2018; McElroy et al. 2019).

2.1 Contamination characteristics of 1,4-dioxane in the water environment

1,4-Dioxane often appears as a co-occurring pollutant in environments contaminated with chlorinated solvents, so some researchers have conducted studies on its environmental behavior in terms of its co-occurrence with chlorinated solvents, including their correlation and comparison of contamination plume distribution.

Studies have shown that the distribution of 1,4-dioxane in water bodies is closely related to chlorinated hydrocarbon pollutants such as 1,1,1-TCA and TCE, especially the 1,1,1-TCA has been used as a chlorinated solvent stabilizer in large quantities and is the main cause of environmental contamination together with 1,4-dioxane. In Kanagawa Prefecture, Japan, Abe's study (1999) showed that 1,4-dioxane was detected in rivers, coastal waters and groundwater. Among them, the detection of 1,4-dioxane in groundwater showing the highest correlation with 1,1,1-TCA ($r = 0.872$) and a weak correlation with TCE ($r = 0.023$). Anderson et al. (2012) quantified the magnitude of 1,4-dioxane contamination in groundwater, via assessing the co-occurrence of 1,4-dioxane with chlorinated hydrocarbon solvents such as 1,1,1-TCA and TCE in selected 4196 groundwater monitoring wells. They stated that in 503 out of 781 groundwater monitoring wells (64.4%) 1,4-diox-

ane was detected to be independently associated with TCE (independent of 1,1,1-TCA). Within different pollution cycles, pollutants are affected by biodegradation, hydrodynamics, and etc. To different degrees, which may be one reason why Anderson's findings are so different from the others. Adamson et al. (2014) evaluated more than 2 000 groundwater sites in California affected by chlorinated solvents and/or 1,4-dioxane and found that at 95% of the 194 sites the 1,4-dioxane was detected to contain one or more chlorinated solvents, mostly in conjunction with 1,1,1-TCA (76% of sites studied). Their subsequent studies showed that there were statistically significant correlations between the concentrations of 1,1-DCA (1,1-dichloroethane) and 1,4-dioxane. However, these studies failed to accurately predict the relationship between these pollutants, which might be influenced by the differences in decay mechanisms (e.g. bio-oxidation pathway for 1,4-dioxane and bio-reduction pathway for 1,1-DCA) and decay rates of both pollutants (Adamson et al. 2017).

Comparing the distribution of 1,4-dioxane with the coexisting chlorinated hydrocarbon contamination plume in groundwater environment, the mobility of 1,4-dioxane is similar to the saturated chlorinated hydrocarbons, but higher than that of unsaturated ones. Many studies have shown that 1,4-dioxane migrates farther than chlorinated solvents (Roy and Griffin, 1985; Priddle and Jackson, 1991; Nyer et al. 1991). Mohr et al. (2001) reported that the 1,4-dioxane contamination plume was six times larger than that of associated solvent. Others have argued that in the absence of DNAPLs, the concentration changes of 1,4-dioxane and TCE are almost parallel (Zenker et al. 2003; Mohr et al. 2010; Stuart et al. 2012; Postigo and Barceló, 2015). Adamson et al. (2014) evaluated more than 2 000 sites affected by chlorinated solvents and/or 1,4-dioxane in California and found that the 1,4-dioxane contamination plume is expected to spread similarly to the TCE contamination plume in most cases. They compared the length distribution of the contamination plumes of 1,4-dioxane and several different chlorinated solvents and found that the 1,4-dioxane contamination plume was longer when all points were considered. In the case of 1,4-dioxane and chlorinated solvents coexisting, only 21% of the 1,4-dioxane contamination plumes were longer than those of corresponding chlorinated solvent, 62% of the chlorinated solvent contamination plumes were longer, and 17% of the two extended to the same length. When 1,4-dioxane, 1,1,1-TCA, TCE and 1,1-DCE (1,1-dichloroethylene) were all present at the same

time, the distribution of the contamination plume lengths of these four compounds was similar, with the 1,4-dioxane contamination plume being shorter than that of TCE and longer than that of 1,1,1-TCA ($p < 0.05$). In terms of concentration variation in a vertical direction, Karges et al. (2018) studied in detail the TCE-contaminated aquifers with 1,4-dioxane as a co-pollutant and showed that the concentration distributions of 1,4-dioxane and TCE were extremely similar in both vertical and horizontal directions, and the two compounds exhibited almost parallel distributions. In fact, unsaturated chlorinated hydrocarbons are subject to bio-chemical degradation and physical adsorption in groundwater environment. The fact that 1,4-dioxane has a similar distribution range to its contamination plume indicates that the mobility of 1,4-dioxane in groundwater is weaker than that of unsaturated hydrocarbons, but much higher than that of saturated chlorinated hydrocarbons, under neglected physicochemical conditions.

1,4-Dioxane is commonly co-occurring with chlorinated hydrocarbons in water bodies, suggesting that its widespread use as a chlorinated solvent stabilizer is one of major sources of environmental contamination. The similarity in the distribution of the contamination plume to the co-occurring chlorinated hydrocarbons may be due to the fact that they are released in similar geochemical environments and migrate along similar groundwater flow paths. The fact that the mobility of 1,4-Dioxane is weaker than unsaturated chlorinated hydrocarbons and stronger than saturated ones may indicate that the attenuation of the unsaturated chlorinated hydrocarbon contaminants cannot be ignored, but this needs to be further investigated. In addition, due to the higher solubility, worse adsorption capacity and higher stability of 1,4-dioxane, it has a more pronounced potential to expand at a later stage, which of course needs further study.

2.2 Attribution characteristics of 1,4-dioxane in the water environment

Due to its strong water solubility, the migration and dilution of 1,4-dioxane are its main attenuation modes in natural water bodies, whilst the volatilization, adsorption and biochemical degradation only account for a small fraction. In surface water, 1,4-dioxane migrates and dilutes rapidly with the water flow. In comparison, natural decay of the 1,4-dioxane in groundwater is much slower because of the limitations in groundwater dynamics. A previous

study by Chiang et al. (2008) showed that the degradation rate of 1,4-dioxane with a 7-year half-life was only 0.099 in groundwater at a site in the southeastern coastal plain of the United States.

It is now generally accepted that there is an upper limit to the attenuation of reductive 1,4-dioxane in groundwater environments, but there is a certain degree of bio-oxidative attenuation. 1,4-dioxane's specific molecular structure makes it resistant to reductive degradation mechanisms (Zenker et al. 2003). Until now, only very limited data is available to show that 1,4-dioxane can be degraded by anaerobic (reductive) mechanisms (Shen et al. 2008). However, a growing amount of evidence suggests that 1,4-dioxane can be attenuated by biological oxidation (Mahendra et al. 2006; Sales et al. 2013; Sei et al. 2013; Huang et al. 2014). Many organisms and enzymes can use 1,4-dioxane as a carbon/energy source to co-metabolize and degrade 1,4-dioxane. However, microbial degradation technology still faces many challenges as regards to environmental remediation for groundwater due to complex hydrological conditions that can affect the growth of microbial degrading bacteria, thus limiting the effectiveness of the application of this technology (Gedalinga et al. 2014; Ma et al. 2015; Li et al. 2015). Adamson et al. (2015) found 1,4-dioxane attenuation at small but numerous sites through a combined assessment of California geotrackers and Air Force monitoring records. At sites where 1,4-dioxane and chlorinated solvents were present, the median source attenuation rate for 1,4-dioxane was lower than 1,1,1-TCA at all statistically significant sites, but was close to 1,1-DCE and TCE. 1,4-dioxane attenuation rates were significantly and positively correlated with those of 1,1-DCE and TCE, but not with TCA. Linear discriminant analysis revealed that 1,4-dioxane attenuation was positively correlated with increasing dissolved oxygen concentration, while it was negatively correlated with metal and CVOC (volatile chlorinated hydrocarbons) concentrations. This suggests that aerobic attenuation of 1,4-dioxane does occur in the groundwater environment, but whether it is only bio-oxidative attenuation is unclear, and its attenuation rate is lower than that of co-occurring chlorinated hydrocarbons.

Many site studies have confirmed that the subsurface environment has a very limited deterrent effect on 1,4-dioxane, reflected by its solubility, environmental stability, and insusceptibility to adsorption. Patterson et al. (1985) found that of the six contaminants (1,4-dioxane, tetrahydrofuran, ether, 1,2-dichloroethane, benzene, and carbon

tetrachloride) existing in the Gloucester landfill, 1,4-dioxane was the most migratory. Based on laboratory column experiments (Priddle and Jackson, 1991), the estimated 1,4-dioxane blocking factor in the Gloucester landfill was 1.1 (Priddle et al. 1991), and based on field monitoring results (Patterson et al. 1985), the blocking factor was 1.4 to 1.6. Liu et al. (2000) used soil from a 1,4-dioxane contaminated site near Durham, North Carolina, and found an average blocking factor of 1.2 for 1,4-dioxane in a column test. Adamson et al. (2016) used a model to investigate the effect of matrix diffusion on the persistence of 1,4-dioxane in contaminated groundwater and concluded that matrix diffusion may have a greater effect on 1,4-dioxane than chlorinated solvents, that the characteristics of 1,4-dioxane favor its large-scale storage within the low-permeability zone of the aquifer, and that matrix diffusion may be a key process in determining the long-term subsurface persistence of 1,4-dioxane.

Much of the previous knowledge on 1,4-dioxane is based on inferences of its physicochemical properties and utilization history, which has limitations and therefore does not fully explain the observed distribution characteristics of its contamination in water environments, especially in groundwater (Mohr, 2001; Zenker et al. 2003; Mohr et al. 2010; Stepien et al. 2014; Adamson et al. 2014; Adamson et al. 2015; Myers et al. 2018). For example, the physicochemical characteristics of 1,4-dioxane suggest that its contamination plume in groundwater should be larger than the associated chlorinated hydrocarbon contamination plume, while the actual findings suggest otherwise. This discrepancy between theory and practice may be due to a combination of emission times and amounts of different contaminants, and physical limitations of groundwater migration. In addition, after releasing the mixed contaminants into the water environment, 1,4-dioxane serves as a co-solvent and thus promotes the dissolution of TCE. This co-solubilization effect enhances the dissolution of mixed contaminants and reduces their sorption capacity in the water environment, thus affecting the migration and remediation of the entire contaminant plume (Milavec et al. 2019). The prevalence of co-occurrence of 1,4-dioxane with chlorinated solvents requires us to enhance the study of the effects of mixtures on contaminant migration in the water environment, especially in groundwater, which appears to be essential for the management and remediation of contaminated plumes.

3 Pollution regulation and control

3.1 Environmental regulation

There is no systematic and effective environmental regulation against the 1,4-dioxane pollution. In the United States, 1,4-dioxane is regulated as a hazardous waste for environmental release only when it is used as an industrial solvent, while its release is not restricted or regulated when used for other purposes (e.g. additives, pesticides, adhesives, etc.) (US EPA, 2011; US EPA, 2017b). Research and routine monitoring of 1,4-dioxane in natural water bodies was gradually carried out in the US by the 1980s, but no corresponding quality standards for the water environment were drawn up. China has banned the use of 1,4-dioxane as a raw material in cosmetics in the Hygienic Standard for Cosmetics (2007 edition), and in 2009, the General Administration of Quality Supervision, Inspection and Quarantine revised the limit of 1,4-dioxane in cosmetics to ≤ 100 mg/kg (as active substance) (Li, 2014; Zhou et al. 2012). In China, there is still a gap in the research on its environmental risk and quality standards, nor has a relevant environmental regulatory standard been established.

In the United States alone, studies have shown that inadequate environmental regulation can lead to significant releases of 1,4-dioxane into the environment. According to the US Chemical Data Reporting Database Toxic Release Inventory (TRI), approximately 320 000 kg of 1,4-dioxane was released to the environment domestically in 2015 (US EPA, 2018a). Due to trade secrets, not all 1,4-dioxane emissions to the natural environment are captured by TRI. Also, the Chemical Data Reporting Database and TRI do not consider the release of 1,4-dioxane as a by-product. Data from US EPA show that approximately 617 000 pounds of 1,4-dioxane used as solvents alone were released in 2017 (US EPA, 2017a; US EPA, 2018b; Pollitt et al. 2019). Other countries, including China, have not yet seen any statistics on environmental releases of 1,4-dioxane. But this figure should not be optimistic. After all, 1,4-dioxane is a widely used chemical raw material.

As 1,4-dioxane has been detected more and more frequently in the natural environment, its contamination of drinking water is gaining attention. 1,4-Dioxane was nominated by the World Health Organization for inclusion in the Guidelines for Drinking Water Quality in 2003, and was included in the US EPA's Contaminant Candidate List 3 in September 2009 (US EPA, 2009). The US

EPA's Unregulated Contaminant Monitoring Rule (UCMR) listed it as a priority for testing from 2013–2015 and found 1,4-dioxane to be the second most common of the unconventional contaminants in public water systems (Adamso et al. 2015; Pollitt et al. 2019). In 2017, the Agency for Toxic Substances and Disease Registry listed 1,4-dioxane as one of the Superfund priority contaminants (#214 of 275 compounds) based on its potential toxic effect and contamination threat to drinking water (ATSDR, 2019).

At present, the world has not formed an effective environmental regulation against the 1,4-dioxane pollution, not to mention establishing enforceable standards for 1,4-dioxane in drinking water, but some developed countries have given non-enforced guidance values (Table 1). In recent years, jurisdictions in the United States have established guideline values for drinking water 1,4-dioxane content ranging from 0.35–77 µg/L. In 2005, the guideline limit for 1,4-dioxane in drinking water was proposed as 50 µg/L in the WHO draft (WHO, 2005), and New Zealand, Korea and Japan followed the WHO standard (An et al. 2014). In Germany, 1,4-dioxane is classified as a

non-regulated toxic substance by the Federal Agency of Environment with a recommended guideline value of 0.1 µg/L (Karges et al. 2018). The wide range of 1,4-dioxane (from 0.1 µg/L to 77 µg/L) in drinking water indicates that there is still a lack of scientific consensus on the impact of low doses of 1,4-dioxane on health, and the content limits of the 1,4-dioxane in drinking water have not formed a unified understanding.

From the above, it can be seen that to establish environmental regulatory standards for 1,4-dioxane pollution, we need to pay attention to the effects of 1,4-dioxane on human health and conduct a lot of researches. This is also a very practical challenge for environmental scientists in China.

3.2 Technology for pollution control

The two symmetrical ether bonds in the 1,4-dioxane molecule make it highly water-soluble, chemically stable and difficult to be biodegraded. This characteristic makes traditional water treatment methods, such as enhanced flocculation, vapor removal, activated carbon adsorption and conventional biological treatment, inefficient in

Table 1 Drinking water guidelines and criteria for 1,4-dioxane (An et al. 2014; US EPA, 2017b; US EPA, 2018a, US EPA, 2018b; Health Canada, 2018; Mulisch et al. 2003; WHO, 2005; Yamamoto et al. 2018)

Jurisdiction	Target concentration /µg/L	Type of target	Year target was introduced
Non-enforced guidance values for 1,4-dioxane in developed countries and WHO			
Canada	50.0	Health Canada, Draft drinking water guidelines	2018
United States	0.35	US EPA, Screening levels for tap water ^a	2017
Korea	50.0	Ministry of the environment, Provisional standards	2014
Japan	50.0	Water pollution control Law, Drinking water standards	2009
Germany	0.1	EPA, Recommended guidance	2003
WHO	50.0	Guidance value	2005
Non-mandatory guidance values for 1,4-dioxane by US states			
New York	1.0	Draft minimum standards	2018
Michigan	7.2	Drinking water standards	2017
Alaska	77.0	Groundwater purification level	2016
Texas	9.1	Protection concentration level	2016
Maine	4.0	Guidance value	2016
Indiana	4.6	Groundwater screening level	2016
North Carolina	3.0	Drinking water standards	2015
New Jersey	0.4	Groundwater quality standards	2015
Connecticut	3.0	Intervention level	2013
Minnesota	1.0	Health risk limits	2013
California	1.0	Public health protection concentration	2011
Massachusetts	0.3	Guidance value	2004

^a The US EPA has not set a minimum level of enforceable standards.

removing it. Municipal wastewater treatment plants are also powerless against this pollutant (Zenker et al. 2002; Stepien et al. 2014). Chlorine disinfection is a traditional method for treating organic pollution in water bodies, which is effective in treating 1,4-dioxane but produces a variety of by-products with higher toxicity. Therefore, for the treatment of 1,4-dioxane contamination in the water environment (mainly groundwater and drinking water sources), scientists have done various experiments and research.

The main feasible and practical technologies for the treatment of 1,4-dioxane contamination are extraction-treatment technology, advanced oxidation process, modified biological treatment and phytoremediation (Barajas-Rodriguez et al. 2019; Yan et al. 2019; Li et al. 2021; Osama et al. 2020).

The pump and treatment technology is suitable for the site with high pollutant concentration, wide range and deep burial (Fei et al. 2022). The low holdup factor of 1,4-dioxane greatly increases its ability to contaminate groundwater and also increases the effectiveness of treatment using extraction-treatment techniques (Jackson and Patterson, 1989; Liu et al. 2000), so when selecting extraction-treatment techniques to treat groundwater contaminated by 1,4-dioxane, it is important to prioritize groundwater dynamic conditions and contamination dispersion time.

Chemical oxidation technology is to oxidize organic pollutants to harmless or less toxic compounds through redox reactions. Among the many directions of treating 1,4-dioxane pollution, there have been numerous studies on chemical oxidation technologies, and scientists have not only conducted in-depth studies on the influencing factors (e.g. initial concentration of 1,4-dioxane, oxidation factors, time, water chemistry conditions, etc.), but also combined electrochemistry, photochemistry, and acoustochemistry, with chemical oxidation techniques to derive various enhanced chemical oxidation technologies. The processes of Fenton reagent, UV plus hydrogen peroxide, ozone plus hydrogen peroxide, electrochemical oxidation, photocatalytic oxidation to generate hydroxyl radicals, and the process of persulfate excitation to generate sulfate radicals are able to effectively degrade 1,4-dioxane (Yang et al. 2021; Flis, 2021; Liu et al. 2020; Matsushita et al. 2019; Zhou et al. 2021; Xue et al. 2021). Among them, the activated persulfate method is increasingly favored for 1,4-dioxane site remediation due to its high stability, relatively low cost, long half-life, wide pH range, less clogging, and more suitable for in situ remediation. The chemical oxidation techno-

logy has the advantages of high efficiency and short time, but in practical application, it needs to consider the operation cost, chemical residues and the possible secondary pollution.

The conventional biological treatment systems do not have very high removal rates for 1,4-dioxane (Abe, 1999), but some current studies have shown that improved biological treatment methods can do better (Roy et al. 1995; Zenker et al. 2002; Daisuke et al. 2021). A variety of bacteria can effectively degrade 1,4-dioxane in water, and they can use 1,4-dioxane as a carbon source or co-metabolize and degrade 1,4-dioxane with other carbon sources (Parales et al. 1994; Zenker et al. 2003; Huang et al. 2014; Pornwongthong et al. 2014; Sekar et al. 2014; Lee et al. 2014; Daisuke et al. 2020; Adamson et al. 2022). However, the application of this technology to environmental remediation of groundwater still faces many challenges, as complex hydrogeological conditions can affect the growth of microbial degrading bacteria, thus limiting the effectiveness of the technology.

Plants can utilize, decompose and transform pollutants, and phytoremediation technologies can take advantage of this nature to achieve detoxification and decomposition of inorganic and organic pollutants. However, phytoremediation techniques are affected by many factors such as climate, plant root depth and balanced groundwater recharge, especially by the depth of groundwater level. The application of phytoremediation technology alone to treat 1,4-dioxane contaminated water still has limitations, but this approach can complement traditional engineering techniques. Compared to engineering-based remediation techniques, phytoremediation is low-cost and environmentally friendly, but it is difficult to determine the criteria, timing, and efficiency of remediation success for the allocation of phytoremediation (Heather, 2013).

4 Prospects and recommendations

From the existing studies, developed countries have already paid attention to 1,4-dioxane pollution as an associated environmental problem of chlorinated solvent pollution at an early stage. Although the relevant research of the 1,4-dioxane pollution is yet insufficient, some achievements have been made in its environmental behavior and pollution management. As China gradually attaches importance to environmental protection and ecological civilization, we will also pay more attention to some non-mainstream pollutants, including the 1,4-dioxane, and make great efforts to treat the environmental problems caused by

them. Therefore, the investigation of the current situation of environmental pollution caused by 1,4-dioxane, the understanding of its environmental behavior and mechanism of action, its toxicological effects and toxicological parameters, and the study of targeted and cost-effective treatment technologies will be the important part of environmental science work in recent years.

(1) Investigation and evaluation of the water environment pollution of 1,4-dioxane are urgently needed. The environmental pollution of 1,4-dioxane in China is not given much attention, and the previous environmental pollution surveys seldom mentioned it, resulting in the environmental pollution status of 1,4-dioxane in natural water bodies, especially in groundwater bodies, which is still unclear. Studies have shown that 1,4-dioxane in the water environment has a series of problems such as multiple pollution sources, easy migration, wide distribution and an imperfect regulatory system. Therefore, attention to 1,4-dioxane environmental pollution should be strengthened and 1,4-dioxane pollution indicators should be added to the water environment survey to acquire the pollution status of 1,4-dioxane in China's water environment (especially the water supply system).

(2) Scientific understanding of the fate behavior of 1,4-dioxane in water and soil environments and its mechanisms is still lacking. The behavior of 1,4-dioxane in the water environment is currently poorly understood and is mainly based on inferences of its chemical characteristics. The following research directions are urgently needed and will lead to breakthroughs: ①How 1,4-dioxane is migrated and transformed in the water environment and its mechanism; ②Mechanisms of biochemical oxidative degradation of 1,4-dioxane in water and soil environments; ③When 1,4-dioxane and its co-occurring chlorinated hydrocarbon solvent are co-existing in the water environment, the effect of the latter on the environmental behavior of the former; ④Toxicological study of 1,4-dioxane and its health risk parameters; ⑤Research and development of economical and efficient remediation technology for 1,4-dioxane pollution, etc.

(3) Environmental standards for 1,4-dioxane and its regulatory system need to be established urgently. Due to insufficient attention, no scientific environmental regulatory system for 1,4-dioxane has been established worldwide. And the significant differences in guidance values for 1,4-dioxane in the water environment suggest that we currently lack scientific consensus on the health effects of low doses of 1,4-dioxane. Therefore, there are still more gaps in scientific understanding and regulatory standards in terms of the carcin-

ogenic risk of 1,4-dioxane and its mechanism, exposure assessment, and environmental standards development. Environmental science researchers should focus on the above-mentioned directions.

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