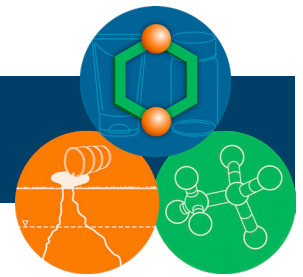




Remediation and Treatment Technologies

1,4-Dioxane



1 Introduction

The chemical and physical properties of 1,4-dioxane (Chemical Abstracts Service [CAS] Registry Number #123-91-1) affect the remediation and treatment options. 1,4-Dioxane is miscible in water, is chemically stable, and does not hydrolyze under typical conditions. It does not adsorb readily to organic carbon (low log K_{oc}), and it has low volatility in an aqueous solution (low Henry's law constant). These properties can lead to the formation of large, diffuse plumes of 1,4-dioxane in groundwater (GW). For additional information regarding the properties of 1,4-dioxane, see the *Environmental Fate, Transport, and Investigation Strategies* fact sheet.

These chemical and physical properties render certain conventional remediation and treatment approaches (such as granular activated carbon, air stripping, and soil vapor extraction) ineffective for 1,4-dioxane. Additionally, these chemical and physical properties render conventional unit processes involved with drinking water (DW) and wastewater (WW) treatment (for example, coagulation, aeration, and chlorination) ineffective for 1,4-dioxane. 1,4-Dioxane is biodegradable under aerobic conditions either by direct metabolism or co-metabolism, but the respective roles of these processes depend on both the concentration of 1,4-dioxane and the presence of common chlorinated co-contaminants, such as 1,1,1-trichloroethane (1,1,1-TCA) and 1,1-dichloroethene (1,1-DCE) (Barajas-Rodriguez and Freedman 2018, Mahendra, Grostern, and Alvarez-Cohen 2013). For co-metabolism, the presence of a suitable primary substrate is also required. In contrast, currently only limited evidence supports anaerobic 1,4-dioxane biodegradation (Shen, Chen, and Pan 2008), and anaerobic bioremediation processes that treat chlorinated solvents (such as trichloroethylene [TCE] and tetrachloroethylene [PCE]) are not anticipated to be effective for 1,4-dioxane. This is important because 1,4-dioxane is commonly comingled with chlorinated solvents in GW.

The Interstate Technology and Regulatory Council (ITRC) has developed a series of six fact sheets to summarize the latest science and emerging technologies regarding 1,4-dioxane. The purpose of this fact sheet is to:

- describe the factors that affect 1,4-dioxane remedy selection
- provide an overview of technologies and methods for treatment of 1,4-dioxane
- summarize the effectiveness and state of development for select technologies

Note: ITRC is developing a 1,4-dioxane guidance document for publication in late 2020. The guidance document will provide additional details on 1,4-dioxane remediation and treatment technologies.

2 Ex Situ and In Situ Remediation and Treatment

The main components of this fact sheet include information on both ex situ and in situ remediation and treatment technologies:

- Figure 1 defines the classification of technologies based on development status and treatment effectiveness.
- Figure 2 illustrates where technologies may be implemented across a 1,4-dioxane plume.
- Table 1 describes ex situ remediation and treatment technologies for GW, DW, and WW.
- Table 2 describes in situ remediation and treatment technologies.

This fact sheet classifies technologies in three levels based on technology development status and treatment effectiveness (see Figure 1). These categories are a quick and useful reference on the relative value of technologies for 1,4-dioxane treatment. *Please note that these categories are based on current knowledge of demonstration as of the date listed on the fact sheet.*

Remediation and Treatment Technologies: 1,4-Dioxane *continued*

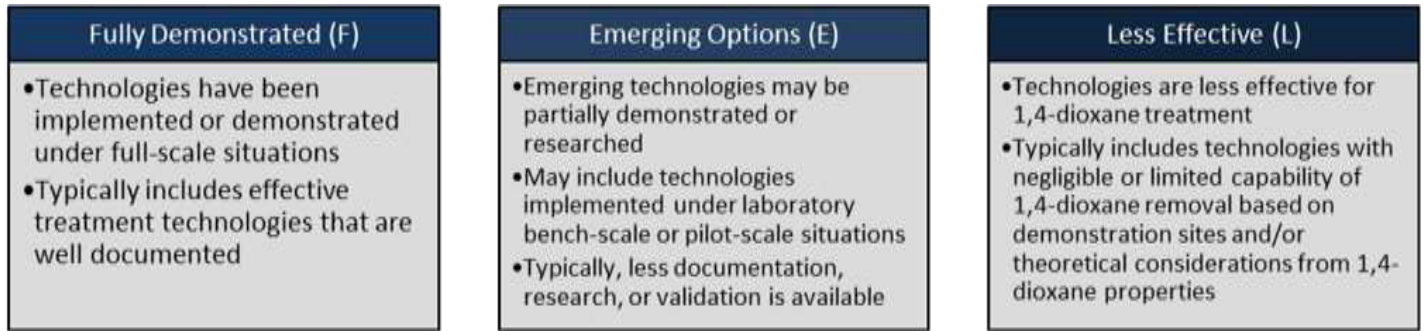
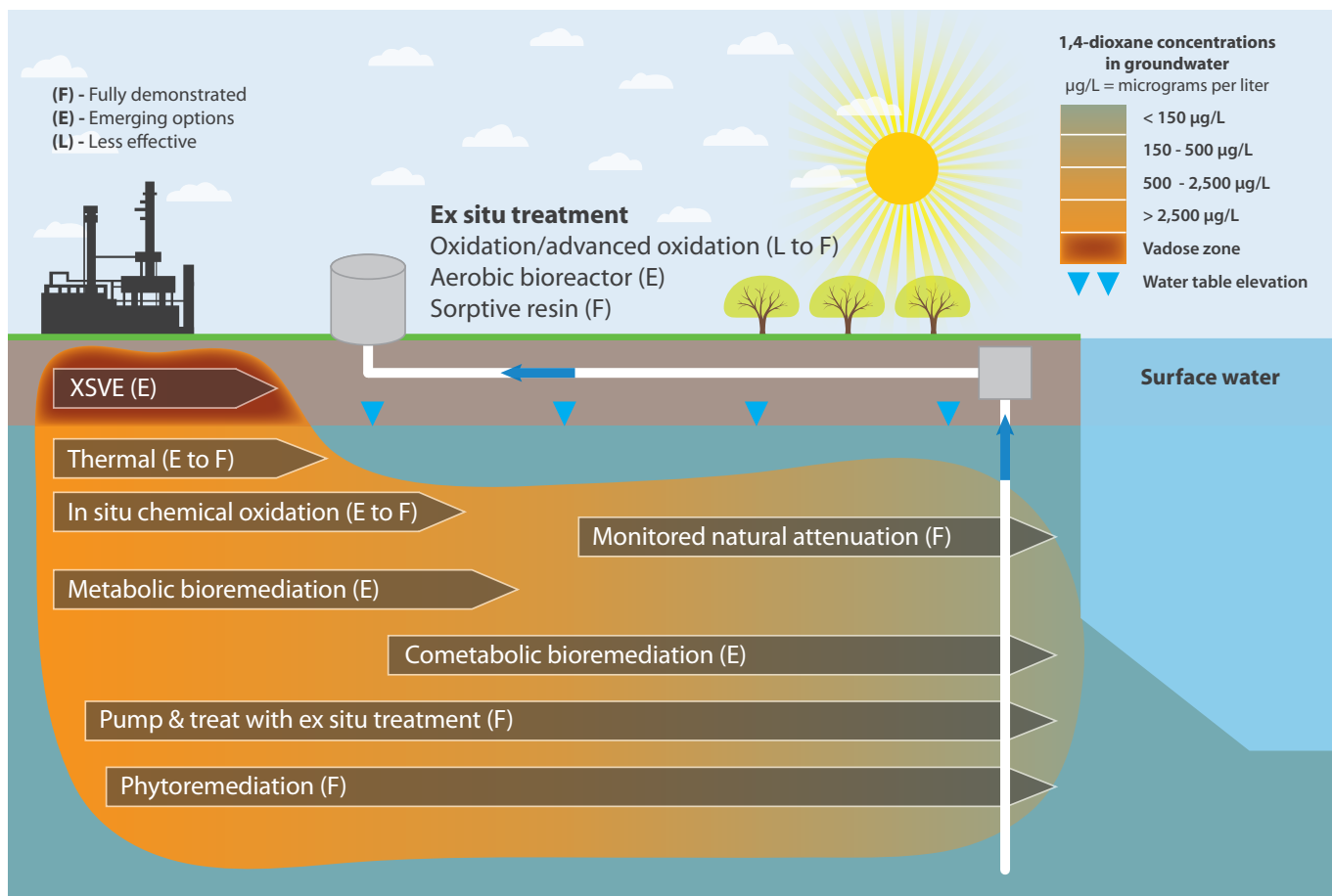


Figure 1. Classification of technologies.

Figure 2 includes remediation and treatment technologies that have been classified as Fully Demonstrated (F) or Emerging Options (E) in certain applications. The figure illustrates where these technologies may be implemented across a 1,4-dioxane plume. Note that the areas shown are schematic in nature, and certain technologies can be effective across a range of locations and concentrations. The actual deployment location of a technology will depend on site-specific conditions.



This figure illustrates where various technologies may be implemented across a 1,4-dioxane plume. It should be noted that the areas shown are schematic in nature, and certain technologies can be effective across a varying range of locations and concentrations. The actual deployment location of a technology will depend on site-specific conditions.

Figure 2. Implementation of technologies.

Remediation and Treatment Technologies: 1,4-Dioxane *continued*

Tables 1 and 2 include a description of the matrix application, treatment effectiveness, advantages, and disadvantages. Note that these technologies can be used alone or in combination; combining them may increase their effectiveness. A technology's effectiveness depends on site-specific conditions, including but not limited to geochemistry and hydrogeology.

Table 1. Ex situ treatment technologies

| Remediation/Treatment Technology* | Development status | | | Effectiveness | Advantages | Disadvantages | Refs [†] |
|---|--------------------|------------------------------------|-----------------------|--|---|---|-------------------|
| | GW | DW | WW | | | | |
| Oxidation/advanced oxidation: UV/hydrogen peroxide | F | F | F | Effective at breaking down 1,4-D to <1 µg/L across a wide range of starting concentrations | Breaks down both cVOCs and 1,4-D. No potential bromate formation in waters with bromide. Capable of continuous treatment at various flow rates. | Requires higher water quality or pretreatment. High electrical usage. | 1, 3, 5 |
| UV/titanium dioxide catalyst/oxidant | F | F | F | Effective at breaking down 1,4-D to <1 µg/L across a wide range of starting concentrations | Breaks down both cVOCs and 1,4-D. No potential bromate formation in waters with bromide. Capable of continuous treatment at various flow rates. | Requires higher water quality or pretreatment. High electrical usage. Catalyst is sensitive to inactivation. | 1, 3, 5 |
| Ozone/hydrogen peroxide | F | F | F | Effective at breaking down 1,4-D to <1 µg/L across a wide range of starting concentrations | Breaks down both cVOCs and 1,4-D. Less sensitive to poor water quality. Lower power consumption compared to UV-based technologies. Capable of continuous treatment at various flow rates. | Potential bromate production in waters with bromide. Wide fluctuations in concentrations pose a problem. Higher chemical usage than UV-based technologies. | 1, 3, 5 |
| UV/ozone/hydrogen peroxide | F | F | F | Effective at breaking down 1,4-D to <1 µg/L across a wide range of starting concentrations | Breaks down both cVOCs and 1,4-D. Capable of continuous treatment at various flow rates. | Requires higher water quality or pretreatment. High electrical usage. | 1, 3, 5 |
| Ozone alone | L | L | L | Poor removal | Less costly than other ozone-based technologies, because other oxidants aren't included | By itself, not a strong enough oxidant to break down 1,4-D, although some studies suggest it may be possible. Potential bromate production in waters with bromide. | 8 |
| Electrochemical | E | E | E | Effective at breaking down 1,4-D to <1 µg/L across a wide range of starting concentrations | Breaks down both cVOCs and 1,4-D. No need for chemical addition. More effective at higher 1,4-D concentrations (~1,000 mg/L). | Cost may be prohibitive. Limited examples of various conditions/scales. Forms disinfection byproducts. | 2, 7 |
| Aerobic bioreactor | E | L | F | Degrades 1,4-D at high (mg/L; metabolic/co-metabolic) and low (µg/L; co-metabolic) starting concentrations; however, extent of removal varies based on mechanism | Degrades 1,4-D via metabolic or co-metabolic mechanisms. Low (i.e., <1 µg/L) effluent concentrations can be met. | Influent water quality may affect removal rate. System upsets may impact performance. | 1, 4, 5 |
| Sorptive resin (e.g., Ambersorb™) | F | E | E – landfill leachate | Removes 1,4-D at high (mg/L) and low (µg/L) starting concentrations to <0.3 µg/L | Designed with specificity and selectivity for 1,4-D removal. Capable of continuous treatment at various flow rates. | Does not break down 1,4-D. Creates waste stream that requires management, and water quality may affect media regeneration capability. | 3, 9 |
| Activated carbon | L | L - large scale E - small scale | NA | Not generally effective due to low sorption; however, somewhat effective at low flow rates | Commonly applied to cVOCs. Readily implemented/available. Use of GAC for point-of-entry treatment can be applied with appropriate monitoring and changeout frequency. | Poor 1,4-D removal due to limited sorption. 1,4-D breaks through before cVOCs. Does not break down 1,4-D. Creates waste stream that requires management. | 1, 3, 5 |
| Air stripping | L | L | L | Not effective without significant adjustments | Commonly applied to cVOCs. Readily implemented/available. | Poor 1,4-D removal | 1, 3 |
| Ion exchange resins | L | L | L | Not effective | Readily implemented/available | Poor 1,4-D removal | 1 |
| Reverse osmosis | L | L | L | Not theoretically effective | Some 1,4-D removal has been reported anecdotally. | The low molecular weight and neutral charge of 1,4-D do not favor removal by reverse osmosis. | 1 |
| Conventional DW/WW/residential treatment trains (e.g., coagulation/flocculation, clarification, filtration, activated sludge) | NA | L | L | Limited effectiveness (e.g., approximately 50% removal) | Readily implemented/available | Limited number of unit processes expected to remove/degrade 1,4-D; however, use of GAC for point-of-entry treatment can be applied with appropriate monitoring and changeout frequency. | 1, 6, 10 |

* Many of the treatment technologies described here are compatible with a pump-and-treat remedial approach.

† "Table 1 References" section.

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Definitions: µg/L = micrograms per liter; 1,4-D = 1,4-dioxane; cVOCs = chlorinated volatile organic compounds; DW = drinking water; E = Emerging Options; F = Fully Demonstrated; GAC = granular activated carbon; GW = groundwater; L = Less Effective; mg/L = milligrams per liter; NA = not applicable; UV = ultraviolet; WW = wastewater.

Table 2. In situ treatment technologies

| Remediation/Treatment Technology | Development status | | Effectiveness | Advantages | Disadvantages | Refs* |
|--|--------------------|-----|--|---|--|-------------------------------|
| | GW | VZS | | | | |
| Monitored natural attenuation (includes physical, chemical, and biological mechanisms) | F | NA | May be effective at reducing 1,4-D at lower starting concentrations (e.g., <500 µg/L), depending on the time available and relevant attenuation mechanisms | Previously applied for cVOCs. CSIA and qPCR are validated in the lab and being applied in the field to document degradation. | Long-term plume data may not be available at many sites. Aerobic biodegradation process with slow degradation rates—does not biodegrade under anaerobic conditions. CSIA enrichment ratios still being determined. Typically requires multiple lines of evidence to demonstrate. | 1, 5, 8, 9, 13, 18 |
| Phytoremediation | F | F | Effective for a range of starting concentrations (up to >2,500 µg/L) | Previously applied for other contaminants and is applicable for some comingled plumes. Controls plume migration by creating zone of depression. 1,4-D transferred to atmosphere where it breaks down. | High cVOC concentrations or other groundwater constituents may cause phytotoxicity. | 2, 10 |
| In situ chemical oxidation: Sodium persulfate/ potassium persulfate | F | E | Effective at oxidizing 1,4-D to <1 µg/L for high starting concentrations (500 to >2,500 µg/L), depending on proper design and implementation | Can oxidize both cVOCs and 1,4-D and is moderately to highly implementable | NOD competition, potential metal solubilization, and health and safety concerns. Large treatment areas are challenging and/or cost-prohibitive, and heterogeneity leads to variable effectiveness. | 7, 11, 12, 14, 16, 23, 25, 28 |
| Modified Fenton's reagent | F | E | Effective at oxidizing 1,4-D to <1 µg/L for high starting concentrations (500 to >2,500 µg/L), depending on proper design and implementation | Can oxidize both cVOCs and 1,4-D and is moderately to highly implementable. Use of chelated iron eliminates the need for low pH. | NOD competition, potential metal solubilization, and health and safety concerns. Large treatment areas are challenging and/or cost-prohibitive, and heterogeneity leads to variable effectiveness. Activation required. Short-lived in subsurface. | |
| Ozone alone | E | E | Effective at oxidizing 1,4-D to <1 µg/L for high starting concentrations (500 to >2,500 µg/L), depending on proper design and implementation | Can oxidize both cVOCs and 1,4-D and is moderately to highly implementable | NOD competition, potential metal solubilization, and health and safety concerns. Large treatment areas are challenging and/or cost-prohibitive, and heterogeneity leads to variable effectiveness. Short-lived in subsurface. Continuous operation required. | |
| Ozone/hydrogen peroxide | E | E | Effective at oxidizing 1,4-D to <1 µg/L for high starting concentrations (500 to >2,500 | Can oxidize both cVOCs and 1,4-D and is moderately to highly implementable. Addition of | NOD competition, potential metal solubilization, and health and safety concerns. Large treatment areas are | |

Remediation and Treatment Technologies: 1,4-Dioxane *continued*

| Remediation/Treatment Technology | Development status | | Effectiveness | Advantages | Disadvantages | Refs* |
|---|--------------------|-----|--|--|---|------------------|
| | GW | VZS | | | | |
| | | | µg/L), depending on proper design and implementation. | hydrogen peroxide can increase radical formation and degradation rates. | challenging and/or cost-prohibitive, and heterogeneity leads to variable effectiveness. Activation required. Short-lived in subsurface. | |
| Sodium permanganate/potassium permanganate | E | E | Effective at oxidizing 1,4-D to <1 µg/L for high starting concentrations (500 to >2,500 µg/L), depending on proper design and implementation | Can oxidize both cVOCs and 1,4-D and is moderately to highly implementable | NOD competition, potential metal solubilization, and health and safety concerns. Large treatment areas are challenging and/or cost-prohibitive, and heterogeneity leads to variable effectiveness. Slow kinetics require high concentrations, long contact time, and low NOD. | |
| Metabolic bioremediation (aerobic) | E | E | Degrades 1,4-D at high starting concentrations (500 to >2,500 µg/L); low concentrations (<100 µg/L) may not stimulate growth | Effective for higher starting concentrations (mg/L) and does not require injection of a primary substrate | Bioaugmentation may be required, and limited microbial transport may be a concern. Technology requires maintenance of aerobic conditions, and cVOCs may inhibit biodegradation. | 3, 4, 17, 20, 21 |
| Co-metabolic bioremediation (aerobic) | E | NA | Degrades 1,4-D to <1 µg/L at high starting concentrations (up to 2,500 µg/L), but more advantageous at low (<100 µg/L) starting concentrations | Can degrade both cVOCs and 1,4-D. Several viable primary substrates. Applicable to dilute plumes. | Bioaugmentation may be required, and flammable gases are typically applied as primary substrate. Technology requires maintenance of aerobic conditions, and cVOCs may inhibit biodegradation. | 6, 14, 19, 21 |
| Thermal: Electrical resistive heating | F | F | | Removes 1,4-D and cVOC DNAPL. Applicable to vadose and saturated zones. | Challenging and costly to implement. Creates waste stream that requires management. Limited effectiveness in the vadose zone. | |
| Steam-enhanced extraction | E | E | Removes 1,4-D at high (500 to >2,500 µg/L) starting concentrations. Extent of removal may vary. | Removes 1,4-D and cVOC DNAPL. Applicable to vadose and saturated zones. Exhibits lower energy demand and shorter treatment time than others. | Challenging and costly to implement. Creates waste stream that requires management. Limited effectiveness in low-permeability lithology. | 22 |
| Thermal conductive heating | E | E | | Removes 1,4-D and cVOC DNAPL. Applicable to vadose and saturated zones. | Challenging and costly to implement. Creates waste stream that requires management. | |
| Extreme/enhanced soil vapor extraction† | NA | E | Removes 1,4-D at high starting concentrations. Extent of removal may vary. | Treats both cVOCs and 1,4-D | May require significant heat addition and larger system components (e.g., blower). Creates waste stream that requires management. | 15 |
| Air sparging/soil vapor extraction | L | L | Not effective, because 1,4-D does not readily partition into gaseous phase | Commonly applied for cVOC treatment | Poor 1,4-D removal | 5 |
| Anaerobic bioremediation | L | NA | Effective in one laboratory study but not reproducible in other studies | Commonly applied for cVOC treatment | Ineffective for 1,4-D treatment | 26 |
| Zero-valent iron | L | L | Does not break down 1,4-D | Commonly applied for cVOC treatment | Ineffective for 1,4-D treatment | 27 |

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† Extreme/enhanced soil vapor extraction was solely developed for 1,4-dioxane treatment; due to its importance, this is the only soil technology included in this table.

Definitions: CSIA = compound-specific isotope analysis; DNAPL = dense nonaqueous phase liquid; NOD = natural oxidant demand; qPCR = quantitative polymerase chain reaction; VZS = vadose zone soil.

5 References

The references cited in this fact sheet, and the other ITRC 1,4-Dioxane fact sheets, are included in one combined list that is available on the ITRC web site.

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