Review Paper

Legacy 1,2,3-trichloropropane contamination: a systematic review of treatments

B. Hope Hauptman and Colleen C. Naughton

ABSTRACT

1,2,3-Trichloropropane (TCP), a suspected human carcinogen, is a widespread contaminant that leaches into groundwater, where it persists. This systematic review of studies examines treatment technologies for TCP contamination. A four-database search yielded 1,160 papers, 36 of which met the eligibility criteria for a full-text review. The three most-represented treatment technologies, such as biodegradation (13), zerovalent transition metals (8), and granular activated carbon (GAC) (4), are either fully deployed in water systems or in the field test stage. To meet TCP treatment goals, additional site-specific testing of well water is needed since source water chemistry and co-contamination influence treatment efficacy. Future studies should include standardized units for reporting degradation or sorption normalized to surface area, chemical input, and/or energy expenditures. Although GAC is the most common treatment for contaminated wells, this technology remains limited due to a low TCP adsorption capacity which requires frequent bed-volume replacement. Aerobic biodegradation, reduction with zerovalent iron, and Fenton's treatment produce byproducts that could limit their use. A geospatial analysis of TCP treatment studies reveals a dearth of knowledge about the extent of TCP contamination. TCP contamination is documented in at least nine countries on three continents, but there is little information about the rest of the world.

Key words | 1,2,3-TCP, granulated activated carbon (GAC), groundwater treatment, legacy contaminant, United Nations Sustainable Development Goal 3 and 6

HIGHLIGHTS

- First systematic review of 1,2,3-trichloropropane (TCP) treatment studies.
- The most highly developed technologies are GAC, zerovalent zinc, and bioremediation.
- Source water chemistry and co-contamination influence TCP treatment efficacy.
- Studies need standardized TCP removal reporting units normalized to the surface area.
- TCP contamination studied in only three continents, revealing wide knowledge gaps.
 Thousands of new substances are added to the Chemical Abstract Service (CAS) registry each day. In 2019, CAS registered its 150 millionth unique substance, 50 million of which were catalogued in the last 4 years alone (Wang 2019). While the manufacture and utilization of new chemical compounds produced is increasing globally, the environmental fate and effects of many of these chemicals are unknown. People living in low- and middle-income countries (LMICs) may be even more vulnerable to an increase in production. Chemical manufacturing companies, which are attracted by low labor costs and lax or absent chemical use and disposal regulations, are increasingly moving their operations to LMICs (Kearns et al. 2019).

As new chemicals are produced and disposed of without consideration for their ultimate fate in the environment, the chances increase that some of these chemicals will cause serious problems for global water quality and public health (Damania et al. 2019). Moreover, water and wastewater treatment plants are not always designed to treat these pollutants, and many will have to take a more costly and reactive ‘end of pipe’ approach to treatment (Alpizar et al. 2019; Mohapatra & Kirpalani 2019). Some of these chemical compounds are recalcitrant, degrading slowly and persisting for long periods, threatening drinking water sources long after their use (Reemtsma et al. 2016). An example is 1,2,3-trichloropropane (TCP), a man-made legacy pollutant banned from use in the United States (U.S.) in 1984, but found in groundwater today (Burow et al. 2019). TCP is a persistent chlorinated hydrocarbon that was previously present in soil fumigants sold under the trade names Telone and D-D as well as an industrial solvent and degreaser. A dense liquid with a low soil organic carbon-water partition coefficient, TCP does not readily sorb to soil. When applied, TCP either evaporates or, because of its high soil mobility, leaches into groundwater (US EPA 2011), where it persists due to a long half-life – estimated at 44–77 years – and low biodegradability (Cheremisinoff & Rosenfeld 2009).

TCP contamination is widespread and detected in groundwater in North America, Europe, and Asia (Kielhorn et al. 2005). In 2011, the European Chemicals Agency put TCP on its Candidate List as a substance of very high concern (SVHC) because it is carcinogenic and toxic to reproduction (ECHA 2011). Although there is no U.S. federal maximum contaminant level (MCL), the allowable amount of a contaminant in drinking water delivered to consumers, TCP was listed on the U.S. Environmental Protection Agency (EPA)’s Contaminant Candidate List 3 (CCL 3) in 2009 (US EPA 2009). Some states including California, Hawaii, and New Jersey have set MCLs for TCP at 5, 600, and 30 ng/L, respectively (US EPA 2017; Torralba-Sanchez et al. 2020). California’s State Water Resources Control Board (SWRCB) demands that out-of-compliance well operators treat water with an approved method, such as granulated activated carbon (GAC), discontinue well use, drill another well, purchase water, consolidate with other...
water systems, and/or dilute contaminated water to concentrations below the MCL (SWRCB 2018).

TCP can also be categorized as a ‘contaminant of emerging concern’, a legacy chemical with newly understood environmental and/or public health consequences (Sauve & Desrosiers 2014). The California SWRCB says that acute exposure to TCP can burn the skin and eyes and that breathing TCP can irritate the throat and lungs and affect concentration, memory, and muscle coordination. Long-term exposure in drinking water may damage the liver and kidneys and increase the likelihood of tumors in multiple organs (US EPA 2017). TCP ingestion has been shown to cause cancer in animals and is believed to be a cancer risk for humans (WHO 2011; SWRCB 2018).

As of 2019, there has not been a systematic review of TCP groundwater treatment studies. Two earlier reviews of TCP treatment options were not systematic (Samin & Janssen 2012; Merrill et al. 2019). Uncertainty remains about how to proceed in the face of expensive monitoring and removal of TCP from public and private wells. The primary goal of this study is to determine the most effective TCP treatment method through a systematic review of the peer-reviewed research. To achieve this goal, this review will: (1) identify which groundwater treatments are being researched for TCP (both field and bench studies); (2) determine how contaminant reduction varies among treatment types; (3) determine chemical byproducts of the different treatments; (4) map research locations and TCP contamination sites; and (5) identify opportunities for future research.

RESULTS AND DISCUSSION

Using 1,2,3-TCP as the single search term in each database produced a total of 1,160 results (Figure 1); and four papers identified in references found in the other eligible papers were also included. All duplicates, a total of 199, were removed. The remaining 965 articles were screened using abstracts and titles, leaving 40 articles that meet the eligibility requirements (inclusion of 1,2,3-TCP and one or more treatment technology). Four papers were excluded because their full text was unavailable (Supplementary Material, Table S11). Overall, this study includes full-text reviews of 36 papers (Table 1).
Spatial distribution and temporal trends in TCP treatment research

In a 2003 report from the World Health Organization, TCP contamination in the hydrosphere was reported in Europe, North America, and Asia (Kielhorn et al. 2003). Globally, TCP concentrations in the hydrosphere range from its detection limit (5 ng/L) to >100,000 ng/L in both ground and surface waters (Table 2 and Figure 2). An objective of this study is to reveal spatial trends in TCP research by mapping where treatment studies are taking place in relation to contamination sites (Figure 2).

Sixty-five percent (23/36) of papers in this study analyze research conducted in the U.S. followed by the Netherlands (14%, 5 papers) (Table 3). The U.S. and the Netherlands have significant groundwater contamination with TCP connected to agricultural application to orchards, vineyards, and potato crops (Samin & Janssen 2012; Babcock et al. 2018). Though none of the TCP research papers was published in South America, Africa, or Australia, the global
| #  | Author (Publication Date)                  | Title                                                                                     | Treatment method or review                  |
|----|-------------------------------------------|-------------------------------------------------------------------------------------------|---------------------------------------------|
| 1  | Vannelli et al. (1990)                    | Degradation of halogenated aliphatic compounds by the ammonia-oxidizing bacterium *Nitrosomonas europaea* | Bioremediation                             |
| 2  | Hunter (1997)                             | Fenton’s treatment of 1,2,3-trichloropropane: chemical reaction byproducts, pathway, and kinetics | Fenton reaction                            |
| 3  | Bosma & Janssen (1998)                    | Conversion of chlorinated propanes by *Methylosinus trichosporium* OB3b expressing soluble methane monooxygenase | Bioremediation                             |
| 4  | Bosma et al. (1999)                       | Utilization of trihalogenated propanes by *Agrobacterium radiobacter* AD1 through heterologous expression of the haloalkane dehalogenase from *Rhodococcus* sp. strain M15-3 | Bioremediation                             |
| 5  | Early et al. (2000)                       | Hydrogen-assisted 1,2,3-trichloropropane dechlorination on supported Pt-Sn catalysts       | Hydrogen-assisted dechlorination            |
| 6  | Bosma et al. (2002)                       | Biodegradation of 1,2,3-trichloropropane through directed evolution and heterologous expression of a haloalkane dehalogenase gene | Bioremediation                             |
| 7  | Klausen et al. (2005)                     | Longevity of granular iron in groundwater treatment processes: solution composition effects on reduction of organohalides and nitroaromatic compounds | ZVI                                        |
| 8  | Huang et al. (2005)                       | Degradation of volatile organic compounds with thermally activated persulfate oxidation | Persulfate                                  |
| 9  | Lim et al. (2007)                         | Sonolysis of chlorinated compounds in aqueous solution                                  | Sonolysis                                   |
| 10 | Monincová et al. (2007)                  | Weak activity of haloalkane dehalogenase LinB with 1,2,3-trichloropropane revealed by X-ray crystallography and microcalorimetry | Bioremediation                             |
| 11 | Tratnyek et al. (2008)                    | Fate and remediation of 1,2,3-trichloropropane                                           | Review                                      |
| 12 | Khan et al. (2009)                        | Effects of iron type in Fenton reaction on mineralization and biodegradability enhancement of hazardous organic compounds | Fenton reaction                            |
| 13 | Pavlova et al. (2009)                     | Redesigning dehalogenase access tunnels as a strategy for degrading an anthropogenic substrate | Bioremediation                             |
| 14 | Yan et al. (2009)                         | Isolation of novel bacteria within the Chloroflexi capable of reductive dechlorination of 1,2,3-trichloropropene | Bioremediation                             |
| 15 | Sarathy et al. (2010)                     | Degradation of 1,2,3-trichloropropane (TCP): hydrolysis, elimination, and reduction by iron and zinc | ZVI, ZVZ                                   |
| 16 | Tratnyek et al. (2010b)                   | Prospects for remediation of 1,2,3-trichloropropane by natural and engineered abiotic degradation reactions | ZVI, ZVZ, Persulfate                       |
| 17 | Salter-Blanc et al. (2012)                | Evaluation of zerolvalent zinc for treatment of 1,2,3-trichloropropane-contaminated groundwater: laboratory and field assessment | ZVZ                                        |
| 18 | Salter-Blanc & Tratnyek (2011)            | Effects of solution chemistry on the dechlorination of 1,2,3-trichloropropane by zero-valent zinc | ZVZ                                        |
| 19 | Samin & Janssen (2012)                    | Transformation and biodegradation of 1,2,3-trichloropropane (TCP)                         | Bioremediation                             |
| 20 | Harada (2014)                             | Comparative evaluation of six different granular activated carbon for TCP removal using rapid small-scale column test | GAC                                        |
| 21 | Kurumbang et al. (2014)                   | Computer-assisted engineering of the synthetic pathway for biodegradation of a toxic persistent pollutant | Bioremediation                             |
| 22 | Li & Shao (2014)                          | Biochemical characterization of a haloalkane dehalogenase DadB from *Alcanivorax dieselolei* B-5 | Bioremediation                             |
reach of companies manufacturing TCP suggests global contamination (Table 3). Analytical methods used to screen for TCP at very low levels have only been in use since 2002 (SWRCB 2011). If more countries pass legislation and set regulatory limits, TCP will be detected in more groundwater supplies and a clearer picture of its distribution will emerge.

In California, hundreds of wells tested above the MCL for TCP (5 ng/L). To determine the national occurrence of TCP contamination, U.S. suppliers tested more than 5,000 drinking water wells between 2013 and 2015 as a part of the U.S. EPA’s Unregulated Contaminant Monitoring Rule 3 (UCMR3). TCP levels in 1.4% of those wells were higher than California’s Public Health Goal (PHG) associated with an elevated cancer risk (10⁻⁶) over a lifetime of exposure. Ninety-seven percent (97%) of TCP detections were in groundwater wells (Porter & Mackey 2018). More updated information is needed to gain a clearer picture of how widespread TCP contamination is in the U.S.

There appears to be an increasing interest in TCP in recent years. In the 5 years between 1990 and 1994, only one TCP treatment study was produced. In contrast, there were 11 studies published in the past 5 years (Figure 3).

### Treatment methods

Of the 36 TCP treatment studies considered for full-text review, 32 were experimental peer-reviewed research papers which fall into two categories: (1) separation-based technologies and (2) degradation-based technologies. The largest number of studies (13, 36%) investigate...
bioremediation using bacteria with enzymatic activity that can degrade TCP. The next most frequent occurrence of studies is on reductive dechlorination with zerovalent iron or zinc (8, 22%) (Figure 4).

The U.S. EPA lists available TCP treatment technologies. Ultraviolet radiation combined with oxidation using potassium permanganate and oxidation processes using ozone are on the EPA’s list. However, none of the papers in this review used these treatments (EPA 2017).

### Bioremediation

Thirteen studies investigate the use of either aerobic or anaerobic biodegradation with strains of bacteria to dechlorinate TCP. Aerobic biodegradation includes cometabolism with monoxygenase enzymes and hydrolysis mediated by haloalkane dehalogenase (Samin & Janssen 2012). Anaerobic biodegradation pathways are reductive dechlorination and dihaloelimination, with TCP as the electron acceptor in both cases (Samin & Janssen 2012). Reductive dechlorination occurs when bacterial enzymes contact chlorinated organic molecules, remove chlorine, and replace it with hydrogen (Samin & Janssen 2012). Dihaloelimination is the replacement of two adjacent chlorine atoms by an additional carbon–carbon bond (Samin & Janssen 2012).

Though GAC-based treatments transfer TCP from a liquid to a solid phase, bioremediation degrades TCP to an innocuous alkane. However, bench-scale tests show that partially chlorinated intermediates may form. In the case of anaerobic degradation, dihaloelimination may produce potentially toxic allyl chloride and allyl alcohol both of which are biodegradable in aerobic and anaerobic conditions (Yan et al. 2009). Toxic products from aerobic co-metabolic degradation using methane monoxygenase include dichloropropanols (Bosma & Janssen 1998). Aerobic hydrolysis with dehalogenases produces 1,3-dichloro-2-propanol and

### Table 2 1,2,3-Trichloropropene distribution in the hydrosphere

| Resource sampled | Continent | Country | Source Information* | Maximum concentration (μg/L) | Study/Agency* |
|------------------|-----------|---------|---------------------|-------------------------------|---------------|
| Drinking Water   | Europe    | Germany | German cities       | 0.1                           | Kielhorn et al. (2003) |
|                  | North America | Mexico  | None stated         | 0.18                          | Gelover et al. (2000)  |
|                  | North America | United States | California (groundwater), Hawaii (groundwater) | 0.24, 0.1 | City of Shafter (2000), Kaua’i Department of Water (2001) |
| Groundwater      | Asia      | Canada, BC | Aquifer in British Columbia | 0.86                           | Zebarth et al. (1998) |
|                  | Asia      | China    | North China Plain   | None provided                 | Li et al. (2015, 2019)  |
|                  | Asia      | Netherlands | Potato Plantations | 5.6                           | Lagas et al. (1989), Kielhorn et al. (2003) |
|                  | North America | United States | California, Hawaii, New York, etc. | 2.7, 2, and >100 | Burow et al. (2019), Oki & Giambelluca (1989), Baier et al. (1987) |
| Surface Water    | Europe    | Germany  | Rivers: Rhein, Emscher, Elbe, and Weser | 0.6                           | Kielhorn et al. (2005) |
|                  | Asia      | Japan    | Rivers: near Osaka  | 100                           | Yamamoto et al. (1997) |
|                  | Asia      | Netherlands | Rivers: Rhein, Meuse, Westerscheldt, and Northern Delta | 2.2                           | Miermans et al. (2000) |
|                  | Slovakia  |          | River: Nitra       | 1.6                           | Frischenschlager et al. (1997) |

*TCP source may be agricultural or industrial.
*From Kielhorn et al. (2003) and included review papers.
2,3-dichloro-1-propanol; however, both are biodegradable (Samin & Janssen 2012).

The most frequently studied treatment method, appearing in 11 of 13 studies, is aerobic enzymatic degradation of TCP, which requires the addition of metabolites (Samin & Janssen 2012). Aerobic methane-oxidizing bacteria, for example, can cometabolize TCP, but only with added propane (Vannelli et al. 1990). Cometabolism indicates that TCP degradation occurs only in the presence of another organic material serving as the primary energy source. These studies investigate three enzymes: methane monooxygenase, propane monooxygenase, and haloalkane dehalogenase (DhaA) (Samin & Janssen 2012). Six of the eleven studies use a genetically engineered bacteria, which improves enzymatic degradation activity of DhaA by one to two orders of magnitude. The specificity constant ($K_{cat}/K_m$) indicates catalytic efficiency and is a convenient way to compare the...
overall ability of an enzyme to convert substrate (in this case TCP) to product (Johnson & Goody 2011). $K_{\text{cat}}/K_m$ values for dehalogenase TCP are reported as high as 1,050 s$^{-1}$ M$^{-1}$ using the genetically engineered dehalogenase enzyme DhaA31 compared with 36 s$^{-1}$ M$^{-1}$ for wild-type strains (Samin & Janssen 2012). In a study using the dehalogenase enzyme LinB (used to degrade the pesticide Lindane), Monincová et al. (2007) report a weak specificity constant 0.068 s$^{-1}$ M$^{-1}$. Although low activity limits its current usefulness as a treatment, the degradation, however small, opens a door to using LinB for future protein engineering studies.

Two studies focus on the anaerobic biodegradation of TCP. In 2009, an anaerobic bacterium called Dehalogenimonas lykanthroporepellens (Dhg) was isolated from a TCP-contaminated petroleum processing superfund site near Baton Rouge, Louisiana, USA. Dhg can use TCP as an electron acceptor, in addition to other chlorinated alkenes. However, bacterial growth required hydrogen as the electron donor. Maximum dechlorination occurred between pH 7 and 7.5 (Yan et al. 2009). A 2017 study at a site in California’s Central Valley shows that Dhg could reduce TCP to meet regulatory levels, even at low initial concentrations (<2 μg/L), and also showed that reduction continued in the field for 15 months post-injection. That study shows that degradation rates are slower, the lower the TCP concentration. Higher inoculum concentrations are needed for reduction, and optimal reduction occurs in a pH range from 7 to 9 (Schmitt et al. 2017).

Zerovoltaic iron and zinc

Eight papers investigated zerovalent metals as reductants, namely iron and zinc to treat water contaminated with TCP. Zerovoltaic zinc (ZVZ) is a more potent reductant than zerovalent iron (ZVI), reducing TCP at rates one to three orders of magnitude faster (Salter-Blanc et al. 2012). ZVZ successfully degrades halogenated alkanes, which includes TCP, of various sizes (Tratnyek et al. 2010a). ZVZ fully reduces TCP to propane which avoids the accumulation of partially reduced products, but when treated with
ZVI, multiple products result, including propane, propylene, and trace amounts of 1-chloro-2-propene (Klausen et al. 2003; Sarathy et al. 2010).

In Li et al. (2015), the authors used nanoscale ZVI powder in addition to a powder made with zinc and found that there was only negligible TCP degradation, with rates so small, the reaction was deemed invalid. Furthermore, Li et al. (2015) concluded that reducing TCP by dechlorination requires a reducing material with a higher surface reactivity than found in ZVI. Additionally, bench tests show that using ZVI to reduce TCP is not feasible due to ZVI’s low reductive capability (Klausen et al. 2003; Sarathy et al. 2010; Li et al. 2015).

In multiple bench-scale experiments using ZVZ, TCP was removed below detection limits (5 ng/L) for samples ranging in concentration from 30 to 10³ micromolar (μM). Kinetics experiments reveal that rate constants normalized for surface area (K_{SA}) were between 10⁻³ and 10⁻² (L·g⁻¹·min⁻¹) (Sarathy et al. 2010; Tratnyek et al. 2006; Salter-Blanc & Tratnyek 2011). The presence of anions and pH can lead to zinc corrosion and influence the efficiency of ZVZ’s TCP reduction ability. Salter-Blanc & Tratnyek (2011) found that in deionized water, TCP degradation rates were the lowest between pH 8 and 10 and greater at higher and lower pH values, showing a u-shaped curve with optimal rates of degradation at pH extremes. However, this trend was not observed in groundwater tests, in which rates were significantly slowed in alkaline groundwater above pH 7, possibly from the development of a passivating film on the zinc surface. These findings may have implications for the long-term effectiveness and practicality of ZVZ treatment technology for contaminated drinking water wells.

**Granular activated carbon**

Hawaii and California have designated GAC adsorption as the Best Available Technology (BAT) to reduce TCP drinking water contamination, but only four research papers in this review focus on GAC. Using carbon to filter out impurities and to neutralize odor and taste in drinking water dates back centuries. GAC filters, which have been used widely in the U.S. for decades (NRC 1980), are composed typically of finely ground particles of wood, coal, or coconut shells that have been heated in the absence of oxygen and/or chemically treated to create highly sorbable surfaces. GAC can sorb multiple pesticides in addition to TCP and, unlike air-stripping, does not emit TCP into the air (Babcock et al. 2018). However, the U.S. EPA says that TCP has a relatively low affinity for GAC (US EPA 2017).

To test GAC treatment feasibility, three of the four studies used Rapid Small-Scale Column Tests (RSSCTs) and isotherm experiments (Harada 2014; Mital 2014; Babcock et al. 2018). RSSCTs demonstrate GAC contaminant removal efficiency with smaller water volumes and shorter contact times than full-scale testing (Crittenden et al. 1986). GAC isotherm tests measure the equilibrium concentration of a specific pollutant in contact with a given sorbent. As such, test results reflect the ability of a particular GAC to remove a specific contaminant. The three TCP GAC treatment studies concluded that the variance in GAC performance may be due to the type of raw material used to make the GAC and to the specific chemistry of the source water matrix, including the presence of organic matter and other contaminants (Harada 2014; Mital 2014; Babcock et al. 2018). The three studies also share some GAC carbon sources – a coal-derived carbon sold by Calgon called Filtrasorb 400 (F400) and Calgon Coconut Shell Carbon (OLC 12 × 40).

Of the GACs tested in wells in Hawaii and California, F400 and OLC 12 × 40 sorbed the greatest amount of TCP before breakthrough to the MCL concentration (5 ng/L), 677 and 676 ng/kg, respectively (Harada 2014; Mital 2014). Jacobi Coconut Shell Carbon was the least effective at TCP removal at all wells tested, regardless of location, by up to one order of magnitude (36–113 ng/kg). No single GAC was effective for all water sources.

Although there was mixed performance, all GAC types lowered TCP effluent concentrations to the 5 ng/L MCL. The total volume of influent treated (number of bed-volumes) can differ by up to one order of magnitude depending on the GAC carbon stock selected (Babcock et al. 2018). Kempisty et al. (2020) used RSSCT to test for reduced sorption due to the presence of other contaminants and dissolved organic matter which often co-occur in groundwater. They calculated the Carbon Use Rate, the mass of carbon needed to treat a volume of water to a target concentration, in this case, 0.5 μg/L. At approximately
0.038 lbs/1,000 gallons treated, a 15-min Empty Bed Contact Time (EBCT) resulted in earlier breakthrough compared with 7.5-min EBCT, due to desorption caused by dissolved organic matter (Kempisty et al. 2020).

GACs are emptied, reactivated, or replaced when breakthrough concentrations are between 10 and 50 ng/L. Harada’s (2014) data also shows that GAC particle size affects performance – the smaller the particle size (mesh size 170×200), the quicker contaminants break through the filtration compared with larger sizes (mesh size 100×120). However, particle size performance may be due to the accuracy of the scaling equations used (Harada 2014). Before the effects of GAC particle size can be fully understood, more information is required.

**Persulfate oxidation**

This review identified four studies that assess activated persulfate’s ability to degrade TCP (Huang et al. 2005; Tratnyek et al. 2010b; Li et al. 2015, 2019). Although the power of mild oxidants (permanganate is one) to degrade TCP is negligible, if the persulfate ion is activated by heat, UV light, ultrasound, or transition metals, the result is a more powerful oxidant. Known as the sulfate-free radical (SO₄•⁻), this oxidant can completely mineralize TCP (Tratnyek et al. 2010b; Li et al. 2015); the bench-scale tests show that the reaction kinetics for TCP degradation in the presence of heat-activated persulfate are similar to other chlorinated ethanes (Tratnyek et al. 2010b). However, Huang et al. (2005) found only 17% TCP degradation in bench testing with heat-activated persulfate.

In 2019, a study achieved 61% TCP degradation rates with Fe²⁺-activated persulfate (Li et al. 2019). Li et al. (2019) tested the in situ injection of Fe²⁺-activated persulfate at the pilot-scale in the North China Plain where TCP had leached into the groundwater from the site of a chemical plant. In bench-scale tests with Fe²⁺-activated persulfate, they achieved 50% reduction of TCP in a 24-h period (Li et al. 2019). But, with pilot-scale tests, TCP degradation efficiency was only 8.3%; presumably, these lower rates resulted from the presence of other contaminants and compounds in the site’s water. Higher reduction rates were seen for aromatic hydrocarbons than in aliphatic hydrocarbons (Li et al. 2019).

**Ammonia treatment**

This review found one study that used an ammonia treatment to degrade TCP in soil (Coyle et al. 2017). As the authors note, deep subsurface in situ ammonia treatments are currently not feasible, but someday they might also be used in TCP-contaminated water (Coyle et al. 2017). Although not in this review, Milchert (2000) demonstrates that ammonolysis can chemically transform waste TCP to 2-chloroallylamine, which is used to manufacture pesticides and pharmaceuticals.

Coyle et al. (2017) report TCP degradation rates ranging from 37 to 65% at 25 °C and from 89 to 94% at 62 °C. Adding dilute ammonia gas (NH₃) to soil raises the pH as it combines with water to produce ammonium and hydroxide ions. This process, called alkaline hydrolysis, has been used to treat soils contaminated with halogenated propanes, explosives, pesticides, and herbicides (Coyle et al. 2017). The high pH values can induce a second round of degradation via activation of the enzyme ammonia monooxygenase, capable of co-metabolic TCP mineralization.

**Fenton’s treatment**

Two papers included in this review apply Fenton’s reaction to degrade TCP (Hunter 1997; Khan et al. 2009). The Fenton reaction uses metal ions to increase the oxygen transfer properties of hydrogen peroxide (H₂O₂) (Babuponnusami & Muthukumar 2014). In acidic conditions, the combination of Fe²⁺/Fe³⁺ or Zn²⁺ and H₂O₂ produces hydroxyl (-OH) radicals capable of degrading TCP. Although highly effective at oxidizing organic pollutants, this reaction requires careful control of conditions such as pH, temperature, and the iron or the zinc/H₂O₂ ratio. In addition, multiple undesirable byproducts are produced with this process: 1,3-dichloropropanone, chloroacetic acid, 2,3-dichloro-1-propene, isopropanol, and propionic aldehyde formic acid among them (Hunter 1997; Khan et al. 2009).

Bench-scale experiments show that TCP mineralization is slow. Hunter (1997) reduced TCP by 95% after 14 days of contact with Fenton’s reagents. The kinetics follow first-order reduction for TCP. Khan et al. (2009) found that given a 20 mg/L solution of TCP in contact with Fenton reagents, 90% of TCP was degraded after 180 minutes and TCP was below detection limits after 240 minutes.
**Sonolysis**

This review included one study investigating the use of ultrasound to mineralize TCP. In ‘Sonolysis of Chlorinated Compounds in Aqueous Solution’, Lim et al. (2007) used batch tests to estimate reaction rates for a variety of chlorinated compounds, including carbon tetrachloride, tri-chloroethylene (TCE), and TCP. Sonolysis has been used to remove volatile organic compounds from water (Mukesh et al. 2022). In solution, ultrasonic waves produce cavitation bubbles which, upon collapse, act as high energy hotspots and produce hydroxyl (-OH) radicals which can oxidize chemical contaminants. The advantage to ultrasound is that it does not require the addition of chemical reagents to capture or degrade pollutants, but it is energy-intensive (Wood et al. 2020).

Lim et al. (2007) show that TCP can undergo thermal combustion (pyrolysis) inside cavitation bubbles and also that reaction rates are optimal at relatively low temperatures (10 °C) and high-power intensity. A pseudo-first-order kinetic model was used to analyze results. Of the three chlorinated compounds tested, TCP had reaction rates most sensitive to higher temperatures, possibly explained by its high activation energy (Lim et al. 2007). Furthermore, depending on the degree of oxidation of the pollutant, undesirable partially oxidized products can be created and require secondary treatment.

**Hydrogen-assisted dichlorination with Pt–Sn catalyst**

In a bench study, Early et al. (2000) investigated the potential for using platinum and tin as catalysts to dechlorinate TCP. They disrupted the carbon–chlorine bond, as per the following two reactions (from Early et al. 2000):

\[
\begin{align*}
\text{CH}_2\text{Cl} & \rightarrow \text{CHCl} + \text{CH}_3 + 3\text{HCl} \\
\text{CH}_2\text{Cl} + \text{HCl} & \rightarrow \text{CH}_2\text{Cl} + \text{H}_2
\end{align*}
\]

Early et al. (2000) explained how changing specific parameters of the kinetics experiments affects the production of byproducts. Their study varied the amounts of C, Pt, and Sn exposed to a reaction mixture of TCP (3,000 ppm) and H₂ (15,000 ppm). Dechlorination products included propane, propene, allyl chloride, and dichloropropene. Catalysts with Pt:Sn ratios of 9:1 and 6:1 exhibited a higher relative hydrogenation activity than monometallic Pt/C. Though Pt/Sn C catalyzed hydrogenation reduced TCP, the Early et al. (2000) study did not establish reaction rates nor removal percentages. In short, the feasibility of Pt/Sn C catalyzed hydrogenation as a treatment technology and for limiting the production of undesirable byproducts has yet to be determined.

**TCP reviews, reports and treatment overviews**

This review found one report (Tratnyek et al. 2010b), one overview (Porter & Mackey 2018), and two reviews of TCP treatments published in peer-reviewed journals (Samin & Janssen 2012; Merrill et al. 2019). Neither of the reviews is systematic and one is focused only on select elimination technologies. A summary of key findings is shown in Table 4.

In a 2010 report for the Strategic Environmental Research and Development Program (SERDP), Tratnyek et al. (2010b) determined rates and products of major types of natural and engineered in situ TCP degradation technologies (with the exception of bioremediation) and investigated optimal zinc selection and reduction conditions. Tratnyek et al. (2010b) found industrial and reagent-grade zinc effective at dechlorinating TCP in deionized water.

The Water Research Foundation (WRF) funded the overview of TCP treatment studies found that air-stripping is not a cost-effective way to meet low regulatory levels (Porter & Mackey 2018). One of the WRF studies evaluated the TCP sorption performance of four different types of GAC and found significant differences in sorption capacity, underscoring the importance of choosing the right GAC carbon stock (Harada 2014; Mital 2014; Babcock et al. 2018). Another WRF study found that temperature plays a role in GAC efficiency, with adsorption capacity at 35 °C approximately 1.5 times the adsorption capacity at 23 °C (Porter & Mackey 2018).

In their 2012 study, Samin & Janssen (2012) reviewed abiotic and biotic TCP transformations and concluded that anaerobic reductive dechlorination may be the best option...
for *in situ* treatment of contaminated water at low concentrations (TCP <1 ng/L). Although aerobic transformations are thermodynamically feasible, co-metabolic transformations can produce toxic products. No naturally occurring aerobic organisms have been found that can oxidize TCP and use it to support growth. This may be due to the rare occurrence of the DhaA gene in nature (Samin & Janssen 2015). However, the construction of recombinant bacterial strains with enhanced DhaA activity (Bosma et al. 2015) may increase the practicality of this technology as a full-scale treatment. Nevertheless, due to low levels of homogenous oxygen in wells contaminated with TCP, *in situ* aerobic transformations of TCP in the subsurface may not be feasible (EPA 2013).

In the most recent review of TCP treatment options, Merrill et al. (2019) found that *in situ* Chemical Reduction (ISCR) and *in situ* Bioremediation (ISB) show the most potential for remediation. ISCR using ZVZ has been tested in the field and in a pilot-scale test at Camp Pendleton in Oceanside, California, where ZVZ was directly injected underground and then monitored. Several ongoing ISB pilot tests at confidential test sites in California’s Central Valley show encouraging results. After an initial 6-month lag phase, ISB reduced TCP concentrations below 5 ng/L (Merrill et al. 2019).

**Identification of TCP treatments**

This study aimed to determine the most effective TCP treatment and/or remediation methods. An objective was to identify the types of groundwater treatments for TCP being researched. Treatments can be broadly divided into separation-based and elimination-based technologies. There is one *ex situ* separation-based technology: GAC, and eight elimination-based technologies: (1) bioremediation, (2) zerovalent zinc, (3) zerovalent iron, (4) persulfate oxidation, (5) Fenton’s treatment, (6) ammonia treatment, (7) hydrogen-assisted dechlorination, and (8) sonolysis.

Because degradation parameters are unique to a specific treatment technology (Table 5), direct comparison of treatment types is difficult. As large wells impacted by TCP may take decades to treat, sustainability should be a reported factor in the ‘success’ of a treatment technology. For example, GAC experimentation involves an RSSCT test to estimate the total number of bed-volumes or empty-bed contact time intervals that different GACs can treat before they are replaced or regenerated. Because of low–moderate sorption affinities between GAC and TCP, TCP removal percentages are high (90–99%). Nevertheless, GAC media replacement rates might be cost-prohibitive (Porter & Mackey 2018). The cost of frequent media

---

**Table 4** | Summary of 1,2,3-trichloropropane treatment reviews and reports

| Author (date) | Number of papers | Research focus | Key findings |
|--------------|-----------------|---------------|-------------|
| Tratnyek et al. (2010b) | n/a | TCP degradation pathways: hydrolysis, elimination, reduction, oxidation | Using reductive chlorination to degrade TCP, ZVZ treatment offers more complete degradation than ZVI |
| | | ZVI, ZVZ, oxidation methods | TCP mineralization achieved with activated persulfate but not with mild oxidants like permanganate |
| Samin & Janssen (2012) | 30 | Natural abiotic degradation and biodegradation | Industrial-grade ZVZ degrades TCP as fast as reagent-grade |
| Porter & Mackey (2018) | n/a | Treatment to meet low regulatory requirements | Full-scale TCP bioremediation is feasible if strains are found or engineered with high activity toward TCP biodegradation |
| Merrill et al. (2019) | 25 | Overview of the benefits and limitations of treatments | GAC seems to be the best available technology for TCP removal; media replacement frequencies will influence design of new treatment facilities |
| | | Specifies research scale | In *situ* chemical reduction (ISCR) and bioremediation (ISB) show the most potential for TCP treatment |
| | | | Since GAC has a low sorption capacity for TCP carbon selection is important. The water matrix influences GAC efficiency, site studies are needed for high removal rates and cost-efficiency |
reduction might especially deter small water treatment systems from adopting this technology (Bereskie et al. 2017).

**Scale of testing and summary of removal information**

Another objective of this review is to determine which TCP remediation methods have been field tested with TCP-contaminated groundwater; those limited to bench tests with water spiked with TCP; those that have undergone pilot testing; and those that are in full-scale operation (Figure 4 and Table 5). GAC is currently in use for TCP removal by at least seven water utilities in California, and some water systems in Hawaii have used GAC for at least 30 years, treating several hundred millions of gallons of water daily (Babcock et al. 2018; Merrill et al. 2019).

While several treatments show verifiable improvement in water quality, others need confirmation (Table 5). Merrill et al. (2019) describe bioremediation pilot tests that succeeded even in wells with low (<2 μg/L) initial concentration of TCP and in raw source water (Merrill et al. 2019). Pilot tests that use ZVZ to reduce TCP also show encouraging results. Direct injection of commercially available ZVZ significantly reduces TCP in groundwater.

Since ZVZ is a powerful oxidant, the occurrence of partially

---

**Table 5 | Summary of articles organized by TCP treatment type**

| Treatment type                  | Number of Papers | Maximum reported removal information | Experimental pH conditions or optimal range (in bold) | Article citations                                                                 | Scale of research |
|---------------------------------|------------------|--------------------------------------|-----------------------------------------------------|-----------------------------------------------------------------------------------|-------------------|
| Bioremediation (aerobic)        | 11               | $K_{cat}/K_m = 1.050 \text{s}^{-1} \text{M}^{-1}$ | 6.9–9.4, 5.5–6.0 and 8.0–9.0 | Vannelli et al. (1990), Bosma & Janssen (1998), Bosma et al. (1999, 2002), Pavlova et al. (2009), Monincová et al. (2007), Kurumbang et al. (2014), Li & Shao (2014), Samin et al. (2014), Gong et al. (2017), Wang & Chu (2017) | Bench             |
| Bioremediation (anaerobic)      | 2                | 0.407 mg/L/day                        | 7.0–7.5, 7–9                                        | Yan et al. (2009), Schmitt et al. (2017)                                            | Bench, Pilot      |
| Zerovalent zinc                 | 6                | Up to 100% (nondetect level) $10^{-3} \text{L m}^{-2} \text{h}^{-1}$ | > 10 or <8 Groundwater <7 | Sarathy et al. (2010), Tratnyek et al. (2010), Salter-Blanc & Tratnyek (2011), Salter-Blanc et al. (2012), Hui et al. (2015), Torralba-Sanchez et al. (2020) | Bench, Pilot      |
| Zerovalent iron                 | 5                | Negligible                            | 9.2 and 11                                          | Vikesland et al. (2003), Sarathy et al. (2010), Hui et al. (2015), Lapeyrrouse et al. (2019) | Bench             |
| Granulated activated carbon     | 4                | 90–99% removal                        | 7–9.8                                               | Mital (2014), Harada (2014), Babcock et al. (2018), Kempisty et al. (2020)          | Bench, Full-scale use |
| Fenton’s treatment              | 2                | 90–90% removal                        | 2–4                                                 | Hunter (1997), Khan et al. (2009)                                                  | Bench             |
| Persulfate oxidation            | 4                | 50% reduction in 24 h; 2.7 × 10^{-6} \text{M}^{-1} \text{s}^{-1} | 2.1–3.0                                            | Huang et al. (2005), Tratnyek et al. (2010), Li et al. (2005, 2019)                | Bench, Pilot      |
| Ammonia Treatment               | 1                | 37–65% at 23 °C and 89–94% at 62 °C | 8–10                                               | Coyle et al. (2007)                                                                | Bench             |
| Hydrogen-assisted dechlorination| 1                | None stated                          | n/a                                                 | Early et al. (2000)                                                               | Bench             |
| Sonolysis                       | 1                | 0.00960 min^{-1}                      | 3                                                   | Lim et al. (2007)                                                                | Bench             |

*If determining optimal pH was a research objective, it is listed in bold. Otherwise, listed pH values were simply stated in the methods.

*Both iron and zinc.
chlorinated byproducts is not observed. Another in situ pilot study reported on the application of activated persulfate in a contaminated site in the North China Plain (Li et al. 2019). TCP degradation was between 30 and 45%, depending on the well, but because sulfate concentrations increased, concerns remain about potential secondary water impacts (Li et al. 2019). Though Fenton's process is effective at oxidizing TCP, no groundwater samples have been tested with this technology (Merrill et al. 2019). Lastly, sonolysis and hydrogen-assisted dechlorination showed success in some bench-level testing, but field tests are needed to confirm TCP degradation in contaminated source water.

Although the natural attenuation of TCP is thought to be minimal under neutral conditions, alkaline conditions and higher temperatures promote TCP hydrolysis (Tratnyek et al. 2003a, 2003b). Since pH influences removal efficiency, studies that include pH conditions in methodology are included in Table 5, and if an objective of the study was to determine the optimal pH range for a particular treatment, it is reported in bold. Additional information regarding pH for each included study is shown in Supplementary Material, Table S11. Except for hydrogen-assisted dechlorination, there was at least one paper in each treatment category that listed the pH conditions of the experiment. Fenton's treatment, persulfate oxidations, and sonolysis occur at low pH conditions; for anaerobic bioremediation, the pH range is closer to neutral (7–7.9). Studies optimizing removal rates of ZVZ as a function of pH show mixed effects. Salter-Blanc & Tratnyek (2011) show two optimal peaks for ZVZ treatment one below pH 8 and the other above pH 10. However, with groundwater samples, pH <7 was optimal possibly due to a passivating surface that may form on zinc in alkaline conditions (Salter-Blanc et al. 2012).

Chemical byproducts

A third objective of this review is to determine if chemical byproducts are produced by different TCP treatment types, and if so, what kinds. Co-metabolic biodegradation using aerobic bacteria, reduction with ZVI, and Fenton's treatment all produce undesirable byproducts that could limit their adoption (Khan et al. 2009; Sarathy et al. 2010; Samin & Janssen 2012). Technologies tested less frequently, such as sonolysis, ammonia treatment, oxidation with strong oxidants, and with hydrogen-assisted dechlorination, have not had a full analysis of their chemical byproducts (Early et al. 2000; Lim et al. 2007; Coyle et al. 2017; Li et al. 2019). Future research may determine if these technologies create undesirable byproducts. Although TCP sorption onto GAC does not cause chemical changes in TCP, it does produce spent materials which either must be regenerated with heat or replaced and disposed of as waste (Harada 2014).

Further research

A final objective of this study is to identify opportunities for future study. Research is needed on changes in microbial populations due to exposure to TCP, the possible byproducts of sonolysis degradation and secondary water quality impacts from the use of activated persulfate treatments. Another area for further research is finding an optimal combination of GAC characteristics to apply to wells contaminated with TCP. Meanwhile, for maximum usability site-specific GAC, TCP removal data should include the presence of co-contaminants, influent and effluent concentrations, bed-volume quantities, and the sorption amount normalized to mass of GAC used (mg/kg) (Supplementary Material, Table S6). Overall, a systematic reporting of contaminate removal data (influent and effluent concentrations, removal percentages, and the use of standard units) would facilitate comparisons of how effective certain technologies are at separating or eliminating TCP from water.

Other than coconut shells, no other agricultural waste product, such as almond shells, which are abundant in California’s Central Valley, has been studied. Such nontraditional, less commercial, and more sustainable carbon alternatives might prove effective. Furthermore, with the exception of the GAC studies, treatment cost comparisons are absent from the literature. Cost and sustainability comparisons would be helpful for LMICS with TCP contamination. The U.S. EPA provides treatment cost worksheets for small (<200 connections) and large (>200 connections) using the work breakdown structure (WBS) model to account for permits, capital costs, and annual operation and maintenance. Current calculators available for GAC vary substantially based on well type, design, location, and flow rate (US EPA 2020). Finally, future research and
monitoring is needed to reveal the extent of TCP contamination in other countries. A limitation of this study may be because searches for this review were performed in English.

**CONCLUSION**

This research supports two United Nations Sustainable Development goals: Goal 6, Clean Water and Sanitation targeting safe and affordable drinking water for all by reducing pollution, and Goal 3, Good Health and Well-being through a reduction in illnesses from pollution (UN 2015). The long-term health consequences of prolonged exposure to TCP are unknown, but experiments indicate that TCP in drinking water is a probable human carcinogen. California has set low limits for TCP – the Maximum Contaminant Levels and Public Health Goals are set as low as 5 and 0.7 ng/L, respectively. Therefore, meeting these low regulatory limits demands efficient, low-cost, and environmentally sustainable treatment technologies.

Of the treatment technologies included in this systematic review, GAC, bioremediation, and ZVZ show the most promise for reducing TCP levels and meeting regulatory requirements for drinking water. GAC is in full-scale use in water systems in Hawaii and California, and anaerobic biodegradation and chemical reduction by ZVZ are in pilot-scale use in California. Although data are limited, strong oxidants like persulfate also appear to remove high levels of TCP (Li et al. 2015). An ammonia treatment is used in only one soil study but shows high rates of TCP degradation (Coyle et al. 2017). In bench and field tests, GAC reduces TCP levels to as low as 5 ng/L in groundwater samples. However, since TCP has a low to moderate adsorption capacity for GAC, the technology requires frequent media replacement and refilling, limiting its practicality. Site-specific testing is necessary to establish co-contaminates and water chemistry for optimal GAC selection to decrease the operational costs of using this technology.

Although no information about TCP contamination was found in South America, Australia, and Africa, there is evidence of widespread global contamination of TCP in the hydrosphere. A complete global map of TCP contamination requires more sampling, testing, and monitoring. Agricultural regions, chemical manufacturing sites, and military establishments are all areas of concern, especially if drinking water is drawn from groundwater.

**ACKNOWLEDGEMENTS**

An undergraduate researcher, Arianna Tariqi, assisted with de-duplication and filtering of abstracts.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

**REFERENCES**

Alpizar, F., Backhaus, T., Decker, N., Eilks, I., Escobar-Pemberthy, N., Fantke, P., Geiser, K., Ivanova, M., Jolliet, O., Kim, H.-S., Khisa, K., Gundimeda, H., Slunge, D., Stec, S., Tickner, J., Tyrer, D., Urho, N., Visser, R., Yarto, M., Zuin, V. G., Zuin, G., Alo, B., Barrantes, V., Makarova, A., Chen, Y., Abdelraouf, M. & Suzuki, N. 2019 Global Chemicals Outlook II: From Legacies to Innovative Solutions: Implementing the 2030 Agenda for Sustainable Development. https://doi.org/10.4337/9781789909975.00006.

Babcock, R. W., Harada, B. K., Lamichhane, K. M. & Tsubota, K. T. 2018 Adsorption of 1,2,3-trichloropropane (TCP) to meet a MCL of 5 ppt. Environmental Pollution 233, 910–915. https://doi.org/10.1016/j.envpol.2017.09.085.

Babuponnusami, A. & Muthukumar, K. 2014 A review on Fenton and improvements to the Fenton process for wastewater treatment. Journal of Environmental Chemical Engineering 2, 557–572. https://doi.org/10.1016/j.jece.2013.10.011.

Baier, J. H., Lykins, B. W., Fronk, C. A. & Kramer, S. J. 1987 Using reverse osmosis to remove agricultural chemicals from groundwater. Journal of the American Water Works Association 79, 55–60. https://doi.org/10.1002/j.1551-8833.1987.tb02894.x.

Bereskie, T., Haider, H., Rodriguez, M. J. & Sadiq, R. 2017 Framework for continuous performance improvement in small drinking water systems. Science of the Total Environment 574, 1405–1414. https://doi.org/10.1016/j.scitotenv.2016.08.067.

Bosma, T. & Janssen, D. B. 1998 Conversion of chlorinated propanes by Methylosinus trichosporium OB3b expressing soluble methane monoxygenase. Applied Microbiology and Biotechnology 50, 105–112. https://doi.org/10.1007/s002530051263.
Bosma, T., Kruizinga, E., De Bruin, E. J., Poelarends, G. J. & Janssen, D. B. 1999 Utilization of trihalogenated propanes by Agrobacterium radiobacter AD1 through heterologous expression of the haloalkane dehalogenase from Rhodococcus sp. strain M15-3. Applied and Environmental Microbiology 65, 4575–4581. https://doi.org/10.1128/aem.65.10.4575-4581.1999.

Bosma, T., Damborsky, J., Stucki, G. & Janssen, D. B. 2002 Biodegradation of 1,2,3-trichloropropane through directed evolution and heterologous expression of a haloalkane dehalogenase gene. Applied and Environmental Microbiology 68, 3582–3587. https://doi.org/10.1128/aem.68.7.3582-3587.2002.

Burow, K. R., Floyd, W. D. & Landon, M. K. 2019 Factors affecting 1,2,3-trichloropropane contamination in groundwater in California. Science of the Total Environment 672, 324–334. https://doi.org/10.1016/j.scitotenv.2019.03.420.

Cheremisinoff, N. P. & Rosenfeld, P. E. 2009 Handbook of Pollution Prevention and Cleaner Production Vol. 2: Best practices in the wood and paper industries. Vol. 3, Chapter 5. pp. 233–246. Elsevier Science, Netherlands. https://doi.org/10.1016/b978-1-4577-7825-0.00003-0.

City of Shafter 2000 Consumer confidence report for water quality. Shafter, CA, City of Shafter, pp. 1–6.

Coyle, C. G., Waisner, S. A., Medina, V. F. & Griggs, C. S. 2017 Use of dilute ammonia gas for treatment of 1,2,3-trichloropropane and explosives-contaminated soils. Journal of Environmental Management 204, 775–782. https://doi.org/10.1016/j.jenvman.2017.03.098.

Crittenden, J. C., Berrigan, J. K. & Hand, D. W. 1986 Design of rapid small-scale adsorption tests for a constant diffusivity. Journal (Water Pollution Control Federation) 58, 312–319.

Damania, R., Desbureaux, S., Rodella, A. S., Russ, J. & Zaveri, E. 2019 Quality Unknown: The Invisible Water Crisis. The World Bank. https://doi.org/10.1596/978-1-4648-1459-4.

Early, K. O., Rhodes, W. D., Kovalchuk, V. I. & D’Itti, J. L. 2000 Hydrogen-assisted 1,2,3-trichloropropane dechlorination on supported Pt-Sn catalysts. Applied Catalysis B: Environmental 26, 257–263. https://doi.org/10.1016/s0926-3373(00)00128-4.

ECHA 2011 Proposals to identify Substances of Very High Concern Previous Consultations. Available from: https://echa.europa.eu/proposals-to-identify-substances-of-very-high-concern-previous-consultations (accessed 18 December 2020).

Frischenschlager, H., Mittermayer, C., Peck, M., Rosenberg, E. & Grasserbauer, M. 1997 The potential of gas chromatography with microwave-induced plasma atomic emission detection (GC-MIPAE) as a complementary analytical technique in environmental screening analysis of aqueous samples. Fresenius’ Journal of Analytical Chemistry 359, 213–221. https://doi.org/10.1007/s002160050563.

Gelover, S., Bandala, E. R., Leal-Ascencio, T., Perez, S. & Martinez, E. 2000 GC-MS determination of volatile organic compounds in drinking water supplies in Mexico. Environmental Toxicology 15 (2), 131–139. https://doi.org/10.1002/(SICI)1522-7278(2000)15:2<131::AID-TOX9>3.0.CO;2-Q

Gong, T., Xu, X., Che, Y., Liu, R., Gao, W., Zhao, F., Yu, H., Liang, J., Xu, P., Song, C. & Yang, C. 2017 Combinatorial metabolic engineering of Pseudomonas putida KT2440 for efficient mineralization of 1,2,3-trichloropropane. Scientific Reports 7 (1), 1–12. doi:10.1038/s41598-017-07435-x.

Harada, B. K. 2014 Comparative Evaluation of Six Different Granular Activated Carbon for TCP Removal Using Rapid Small Scale Column Test. PhD Thesis, University of Hawaii. Available from: http://hdl.handle.net/10125/101082 (accessed 18 December 2020).

Huang, K.-C., Zhao, Z., Hoag, G. E., Dahmani, A. & Block, P. A. 2005 Degradation of volatile organic compounds with thermally activated persulfate oxidation. Chemosphere 61, 551–560. https://doi.org/10.1016/j.chemosphere.2005.02.032.

Hui, L., Zhan-tao, H., Chun-xiao, M. & Jian-ye, G. 2015 Comparison of 1,2,3-trichloropropane reduction and oxidation by nanoscale zero-valent iron, zinc and activated persulfate. Journal of Groundwater Science and Engineering 3, 156–163.

Hunter, F. 1997 Fenton’s treatment of 1,2,3-trichloropropane: chemical reaction byproducts, pathway, and kinetics. In: Chemical Oxidation: Technologies for the Nineties, Vol. 6 (W. W. Eckenfelder, A. R. Bowers & J. A. Roth, eds). USA, pp. 50–71. Available from: https://www.google.com/books/edition/Chemical_Oxidation/T-20PBkl51IC?hl=en&gbpv=1&dq=Fenton%E2%80%99s+treatment+of+1,2,3-trichloropropane:+Chemical+reaction+byproducts,+pathway,+and+kine&pg=PA50&printsec=frontcover (accessed 18 December 2020).

Johnson, K. A. & Goody, R. S. 2011 The original Michaelis constant: translation of the 1913 Michaelis–Menten paper. Biochemistry 50 (39), 8264–8269. https://doi.org/10.1021/bi201284u.

Kauai’s Department of Water 2001 Puhi water system 2001, water quality report. Kauai’s Department of Water, Kauai’s, pp. 1–6.

Kearns, J. P., Bentley, M. J., Mokashi, P., Redmon, J. H. & Levine, K. 2009 Effects of iron type and concentration on Fenton’s treatment of 1,2,3-trichloropropane: a comparative analytical technique in environmental screening analysis of aqueous samples. Journal of Water, Sanitation and Hygiene for Development 9, 786–793. https://doi.org/10.2166/washdev.2019.059.

Kempisty, D. M., Summers, R. S., Abulkem, G., Deshpande, N. v., Rebholz, J. A., Roberts, K. & Pressman, J. G. 2000 Hydrogen-assisted 1,2,3-trichloropropane dechlorination on supported Pt-Sn catalysts. Applied Catalysis B: Environmental 26, 257–263. https://doi.org/10.1016/s0926-3373(00)00128-4.

Khan, E., Wirojanagud, W. & Sermsai, N. 2009 Effects of iron type in Fenton reaction on mineralization and biodegradability enhancement of hazardous organic compounds. Journal of Hazardous Materials 161, 1024–1034. https://doi.org/10.1016/j.jhazmat.2008.04.049.

Kielhorn, J., Konnecker, G., Pohnlenz-Michel, C., Schmidt, S. & Mangelsdorf, I. 2003 Concise International Chemical
Assessment Document 56 – 1,2,3-Trichloropropane. World Health Organization, Geneva. https://doi.org/10.1515/ci.2003.25.121b. Available from: https://www.who.int/ipcs/publications/cicad/en/cicad56.pdf?ua=1.

Klausen, J., Vikesland, P. J., Kohn, T., Burris, D. R., Ball, W. P. & Roberts, A. L. 2005 Longevity of granular iron in groundwater treatment processes: solution composition effects on reduction of organohalides and nitroaromatic compounds. Environmental Science & Technology 37 (6), 1208–1218. doi:10.1021/es040955s

Kurumbang, N. P., Dvorak, P., Bendl, J., Brezovsky, J., Prokop, Z. & Damborský, J. 2014 Computer-assisted engineering of the synthetic pathway for biodegradation of a toxic persistent pollutant. ACS Synthetic Biology 3, 172–181. https://doi.org/10.1021/sb400147n.

Kwon, Y., Lemieux, M., McTavish, J. & Watthen, N. 2015 Identifying and removing duplicate records from systematic review searches. Journal of the Medical Library Association 103, 184–188. https://doi.org/10.3163/1536-5050.103.4.004.

Lagas, P., Verdam, B. & Loch, J. P. G. 1989 Threat to groundwater quality by pesticides in the Netherlands. In: Groundwater Management: Quantity and Quality (Proceedings of the Benidorm Symposium, October 1989). Wallingford, Oxfordshire, Centre for Ecology and Hydrology, International Association of Hydrological Sciences, pp. 171–180 (IAHS Publication No. 188). http://hydrologic.org/redbooks/a188/a188_0171.pdf.

Lapeyrrouse, N., Li, M., Zou, S., Booth, G. & Yestrebsky, C. L. 2019 Remediation of chlorinated alkanes by vitamin B12 and zero-valent iron. Journal of Chemistry 2019. https://doi.org/10.1155/2019/7565464.

Li, A. & Shao, Z. 2014 Biochemical characterization of a haloalkane dehalogenase DdA from Alcanivorax dieselolei B-5. PLoS ONE 9, e89144. https://doi.org/10.1371/journal.pone.0089144.

Li, H., Han, Z., Ma, C. & Gui, J. G. 2015 Comparison of 1,2,3-trichloropropane reduction and oxidation by nanoscale zero-valent iron, zinc and activated persulfate. Journal of Groundwater Science and Engineering 3, 156–163.

Li, H., Han, Z., Qian, Y., Kong, X. & Wang, P. 2019 In situ persulfate oxidation of 1,2,3-trichloropropane in groundwater of north China plain. International Journal of Environmental Research and Public Health 16, 2752. https://doi.org/10.3390/ijerph16152752.

Lim, M. H., Kim, S. H., Kim, Y. U. & Khim, J. 2007 Sonolysis of chlorinated compounds in aqueous solution. Ultrasonics Sonoochemistry 14, 93–98. https://doi.org/10.1016/j.ultsonch.2006.03.003.

Merrill, J. P., Suchomel, E. J., Varadhan, S., Asher, M., Kane, L. Z., Hawley, E. L. & Deeb, R. A. 2009 Development and validation of remediation for remediation of 1,2,3-trichloropropene in groundwater. Current Pollution Reports 5, 228–237. https://doi.org/10.1007/s40726-019-00122-7.

Miermans, C. J. H., van der Velde, L. E. & Frintrop, P. C. M. 2000 Analysis of volatile organic compounds, using the purge and trap injector coupled to a gas chromatograph/ion-trap mass spectrometer: Review of the results in Dutch surface water of the Rhine, Meuse, Northern Delta Area and Westerscheldt, over the period 1992–1997. Chemosphere 40 (1), 39–48. https://doi.org/10.1016/S0045-6535(99)00229-5.

Miklos, D. B., Remy, C., Jekel, M., Linden, K. G., Drewes, J. E. & Hübner, U. 2018 Evaluation of advanced oxidation processes for water and wastewater treatment – a critical review. Water Research 139, 118–151. https://doi.org/10.1016/j.watres.2018.03.042.

Milchert, E. 2000 Ammonolysis of waste 1,2,3-trichloropropane by liquid ammonia. Journal of Chemical Technology and Biotechnology 75, 320–326. https://doi.org/10.1002/(SICI)1097-4660(200004)75:4<320::AID-JCTB222>3.0.CO;2-A.

Mital, J. 2014 Granular Activated Carbon Treatment of 1,2,3-Trichloropropane. MS Thesis, University of California, Davis. Available from: https://search.proquest.com/openview/ccfe0327c51534acc8ae8922bb93218bc/1?pq-origsite=gscholar&cbl=18750&diss=y (accessed 18 December 2020).

Mohapatra, D. P. & Kirpalani, D. M. 2019 Advancement in treatment of wastewater: fate of emerging contaminants. The Canadian Journal of Chemical Engineering 97, 2621–2631. https://doi.org/10.1002/cjce.23533.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G. & Prisma Group 2009 Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Medicine* 6 (7), e1000097. doi:10.1371/journal.pmed.1000097.

Monincová, M., Prokop, Z., Věvodová, J., Nagata, Y. & Damborský, J. 2007 Weak activity of haloalkane dehalogenase LinB with 1,2,3-trichloropropane revealed by X-ray crystallography and microcalorimetry. *Applied and Environmental Microbiology* 73, 2005–2008. https://doi.org/10.1128/AEM.02416-06.

Mukesh, G., Ashutosh, D., Ravikumar, K. & Nagarajan, R. 2012 Sonochemical degradation of volatile and non-volatile compounds. *Research Journal of Chemistry and Environment* 16 (4), 192–199.

National Research Council (NRC) (US) Safe Drinking Water Committee 1980 Drinking water and health, Volume 2. In: Drinking Water and Health: An Evaluation of Activated Carbon for Drinking Water Treatment. The National Academies Press. https://doi.org/10.17226/1904.

Oki, D. S. & Giambelluca, T. W. 1989 Groundwater contamination by nematicides: Influence of recharge timing under pineapple crop. *Water Research Bulletin* 25, 285–294. https://doi.org/10.1111/j.1752-1688.1989.tb03063.x.

Pavlova, M., Pavlova, M., Klvana, M., Prokop, Z., Chaloupkova, R., Banas, P., Otýpek, M. & Damborsky, J. 2009 Redesigning dehalogenase access tunnels as a strategy for degrading an anthropogenic substrate. *Nature Chemical Biology* 5, 727–733. https://doi.org/10.1038/nchembio.205.

Porter, K. L. & Mackey, E. D. 2018 Preparing for change: TCP overview and treatment considerations. *Journal – American
Water Works Association 110, 31–35. https://doi.org/10.1002/awwa.1059.
Reemtsma, T., Berger, U., Arp, H. P. H., Gallhard, H., Knepper, T. P., Neumann, M., Quintana, J. B. & Voogt, P. d. 2016 Mind the gap: persistent and mobile organic compounds – water contaminants that slip through. Environmental Science and Technology 50, 10308–10315. https://doi.org/10.1021/acs.est.6b03338.
Salter-Blanc, A. J. & Tratnyek, P. G. 2011 Effects of solution chemistry on the dechlorination of 1,2,3-trichloropropane by zero-valent zinc. Environmental Science and Technology 45, 4073–4079. https://doi.org/10.1021/es104081p.
Salter-Blanc, A. J., Suchomel, E. J., Fortuna, J. H., Nurmi, J. T., Walker, C., Krug, T., O’Hara, S., Ruiz, N., Morley, T. & Tratnyek, P. G. 2012 Evaluation of zerovalent zinc for treatment of 1,2,3-trichloropropane-contaminated groundwater: laboratory and field assessment. Ground Water Monitoring and Remediation 32, 42–52. https://doi.org/10.1111/j.1745-6592.2012.01402.x.
Samin, G. & Janssen, D. B. 2012 Transformation and biodegradation of 1,2,3-trichloropropane (TCP). Environmental Science and Pollution Research 19, 3067–3078. https://doi.org/10.1007/s11356-012-0859-3.
Samin, G., Pavlova, M., Arif, M. I., Postema, C. P., Damborsky, J. & Janssen, D. B. 2014 A Pseudomonas putida strain genetically engineered for 1,2,3-trichloropropane bioremediation. Applied and Environmental Microbiology 80, 5467–5476. https://doi.org/10.1128/aem.01620-14.
Sarathy, V., Salter, A. J., Nurmi, J. T., O’Brien Johnson, G., Johnson, R. L. & Tratnyek, P. G. 2010 Degradation of 1,2,3-trichloropropane (TCP): hydrolysis, elimination, and reduction by iron and zinc. Environmental Science & Technology 44 (2), 787–793. doi:10.1021/es902595j
Sauve, S. & Desrosiers, M. 2014 A review of what is an emerging contaminant. Chemical Society Journal 8. https://doi.org/10.1016/j.matpr.2013.01.035
Schmitt, M., Varadhan, S., Dworatzek, S., Webb, J. & Suchomel, E. 2017 Optimization and validation of biological reduction of 1,2,3-trichloropropane in groundwater. Remediation 28, 17–25. https://doi.org/10.1002/rem.21539.
SWRCB (Canada State Water Resources Control Board) 2007 General Information Sheet 1,2,3-Trichloropropane (TCP). Div. Water Qual. GAMA Program. Available from: https://www.waterboards.ca.gov/gama/docs/coc_tcp123.pdf (accessed 18 December 2020).
SWRCB (Canada State Water Resources Control Board) 2008 1,2,3-Trichloropropane (1,2,3-TCP) Maximum Contaminant Level (MCL). Div. Drinking Water Branch. Available from: https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/123-tcp/123tcpt_utility_training.pdf (accessed 18 December 2020).
Torralba-Sánchez, T. L., Bylaska, E. J., Salter-Blanc, A. J., Meisenheimer, D. E., Lyon, M. A. & Tratnyek, P. G. 2020 Reduction of 1,2,3-trichloropropane (TCP): pathways and mechanisms from computational chemistry calculations.
Environmental Science: Processes & Impacts 22, 606–616. https://doi.org/10.1039/c9em00557a.
Tratnyek, P. G., Sarathy, V. & Fortuna, J. H. 2008 Fate and remediation of 1,2,3-trichloropropane. In International Conference on Remediation of Chlorinated and Recalcitrant Compounds, 6th Paper C-047. Available from: https://www.researchgate.net/profile/Paul_Tratnyek/publication/228485340_Fate_and_remediation_of_1_2_3-trichloropropane/links/0912f50d23137b7aed000000.pdf (accessed 18 December 2020).
Tratnyek, P. G., Salter, A. J., Nurmi, J. T. & Sarathy, V. 2010a Environmental applications of zerovalent metals: iron vs. zinc. In: Nanoscale Materials in Chemistry: Environmental Applications. ACS Publications, pp. 165–178. https://doi.org/10.1021/bk-2010-1045.ch009.
Tratnyek, P. G., Sarathy, V., Salter, A. J., Nurmi, J. T., Johnson, G. O., DeVoe, T. & Lee, P. 2008b Prospects for remediation of 1,2,3-trichloropropane by natural and engineered abiotic degradation reactions. Strategic Environmental Research and Development Program (SERDP) Project ER-1457 Final Report. Available from: https://www.serdp-estcp.org/content/download/9291/110767/FILE/ER-1457-FR.pdf.
United Nations (UN) 2015 About the Sustainable Development Goals – United Nations Sustainable Development. Sustainable Development Goals. Available from: https://www.un.org/sustainabledevelopment/sustainabledevelopmentgoals/ (accessed 18 December 2020).
U.S. Environmental Protection Agency (EPA) 2009 Contaminant Candidate List 3 – CCL 3. Available from: https://www.epa.gov/ccl/contaminant-candidate-list-3-ccl-3 (accessed 18 December 2020).
U.S. Environmental Protection Agency (EPA) 2013 Introduction to In Situ Bioremediation of Groundwater. Available from: https://www.epa.gov/remeditech/introduction-situ-bioremediation-groundwater (accessed 18 December 2020).
U.S. Environmental Protection Agency (EPA) 2017 Technical Fact Sheet – 1,2,3-Trichloropropane (TCP). Environmental Protection Agency. Available from: https://www.epa.gov/fedfac/technical-fact-sheet-123-trichloropropane-tcp (accessed 18 December 2020).
U.S. Environmental Protection Agency 2020 Drinking Water Treatment Technology Unit Cost Models. Available from: www.epa.gov/sdwa/drinking-water-treatment-technologyunit-cost-models (accessed 29 June 2020).
van Leeuwen, J. G. E., Wijma, H. J., Floor, R. J., van der Laan, J.-M. & Janssen, D. B. 2012 Directed evolution strategies for enantiocomplementary haloalkane dehalogenases: from chemical waste to enantiopure building blocks. ChemBioChem: A European Journal of Chemical Biology 13, 137–148. https://doi.org/10.1002/cbic.201100579.
Vannelli, T., Logan, M., Arciero, D. M. & Hooper, A. B. 1990 Degradation of halogenated aliphatic compounds by the ammonia-oxidizing bacterium Nitrosomonas europaea. Applied and Environmental Microbiology 56,
Vikesland, P. J., Klausen, J., Zimmermann, H., Roberts, A. L. & Ball, W. P. 2003 Longevity of granular iron in groundwater treatment processes: changes in solute transport properties over time. *Journal of Contaminant Hydrology* 64, 3–33. https://doi.org/10.1016/S0169-7722(02)00150-X.

Wang, L. D. 2019 CAS reaches 150 millionth substance. *Chemical 
& Engineering News*. Available from: https://cen.acs.org/acsn-news/programs/CAS-reaches-150-millionth-substance/97/web/2019/05 (accessed 18 December 2020).

Wang, B. & Chu, K. H. 2017 Cometabolic biodegradation of 1,2,3-trichloropropane by propane-oxidizing bacteria. *Chemosphere* 168, 1494–1497.

Wood, R. J., Sidnell, T., Ross, I., McDonough, J., Lee, J. & Bussemaker, M. J. 2020 Ultrasonic degradation of perfluorooctane sulfonic acid (PFOS) correlated with sonochemical and sonoluminescence characterization. *Ultrasonics Sonochemistry* 68, 105196. https://doi.org/10.1016/j.ultsonch.2020.105196.

World Health Organization (WHO) 2011 *1,2,3-Trichloropropane, in Report on Carcinogens: Carcinogen Profiles*. William Andrew Publishing, Oxford, USA, pp. 233–246. Available from: https://www.who.int/ipcs/publications/cicad/en/cicad56.pdf (accessed 18 December 2020).

Yamamoto, K., Fukushima, M., Kakutani, N. & Kuroda, K. 1997 Volatile organic compounds in urban rivers and their estuaries in Osaka, Japan. *Environmental Pollution* 95, 135–143. https://doi.org/10.1016/S0269-7491(96)00100-5

Yan, J., Rash, B. A., Rainey, F. A. & Moe, W. M. 2009 Isolation of novel bacteria within the Chloroflexi capable of reductive dechlorination of 1,2,3-trichloropropane. *Environmental Microbiology* 11, 833–843. https://doi.org/10.1111/j.1462-2920.2008.01804.

Zebarth, B. J., Szeto, S. Y., Hii, B., Liebscher, H. & Grove, G. 1998 Groundwater contamination by chlorinated hydrocarbon impurities present in soil fumigant formulations. *Water Quality Research Journal* 33 (1), 31–50. https://doi.org/10.2166/wqrj.1998.003.

First received 11 January 2021; accepted in revised form 26 March 2021. Available online 9 April 2021