Check for updates

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

B. Hope Hauptman (corresponding author)
Environmental Systems Graduate Group,
University of California Merced,
5200 N. Lake Rd., Merced, CA 95343,
USA
E-mail: *bhauptman@ucmerced.edu*

Colleen C. Naughton
Department of Civil and Environmental Engineering,
University of California Merced,
5200 N. Lake Rd.,
Merced, CA 95343,
USA

HIGHLIGHTS

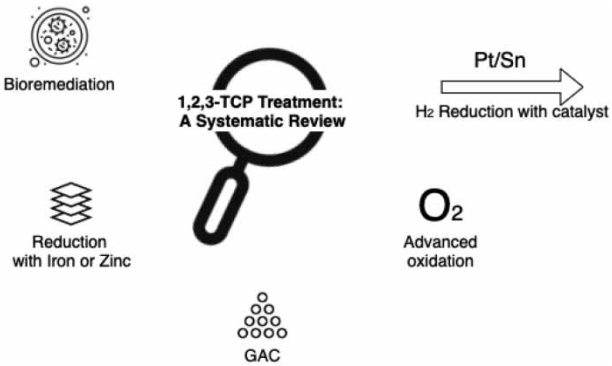
- First systematic review of 1,2,3-trichloropropane (TCP) treatment studies.
- The most highly developed technologies are GAC, zerovalent zinc, and bioremediation.
- Source water chemistry and co-contamination influence TCP treatment efficacy.
- Studies need standardized TCP removal reporting units normalized to the surface area.
- TCP contamination studied in only three continents, revealing wide knowledge gaps.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (http://creativecommons.org/licenses/by/4.0/).

doi: 10.2166/washdev.2021.006

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

GRAPHICAL ABSTRACT



INTRODUCTION

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 2017), 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.* 2003). 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

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

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 contaminate 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.

METHODS

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for systematic reviews (Moher *et al.* 2009). Included in this review are published nonsystematic reviews and research on TCP with special attention to treatment and/or remediation of contaminated water sources. An initial search exposed a variety of studies ranging from the carcinogenic potential and toxicology of TCP to its use as a precursor to epichlorohydrin manufacture (van Leeuwen *et al.* 2012). Four online databases were consulted for this review: Science Direct, Web of Science, PubMed, and Engineering Village. The publication date was not considered as an exclusion factor.

From the total number of results in an initial search, papers were transferred to the citation manager, RefWorks, and de-duplicated manually by two reviewers. To confirm the results, the reviewers manually deleted duplicates after sorting by title, and once again after sorting by author. Although the automatic de-duplicating function within RefWorks has been found to yield the smallest number of false positives (duplicate citations deleted in error) when compared with Mendeley and Endnote de-duplication functions, manual de-duplication produces the fewest de-duplication errors (Kwon *et al.* 2015). After duplicates were removed, two reviewers screened the remaining abstracts, keywords, and titles for the presence of '1,2,3-trichloropropane' and direct reference to any variety of treatment to remove TCP from contaminated water. Research papers were included whether the treatment technology studied was in early bench-scale experimental stages or in full-scale use by water utilities.

Finally, the first author independently read the 36 full-length unique studies and classified each by the treatment method, the percent of contaminate reduction or removal rate, and the location of each paper's primary author. Additional results, identified through the references of selected papers, were added if they met the eligibility requirements above.

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).

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

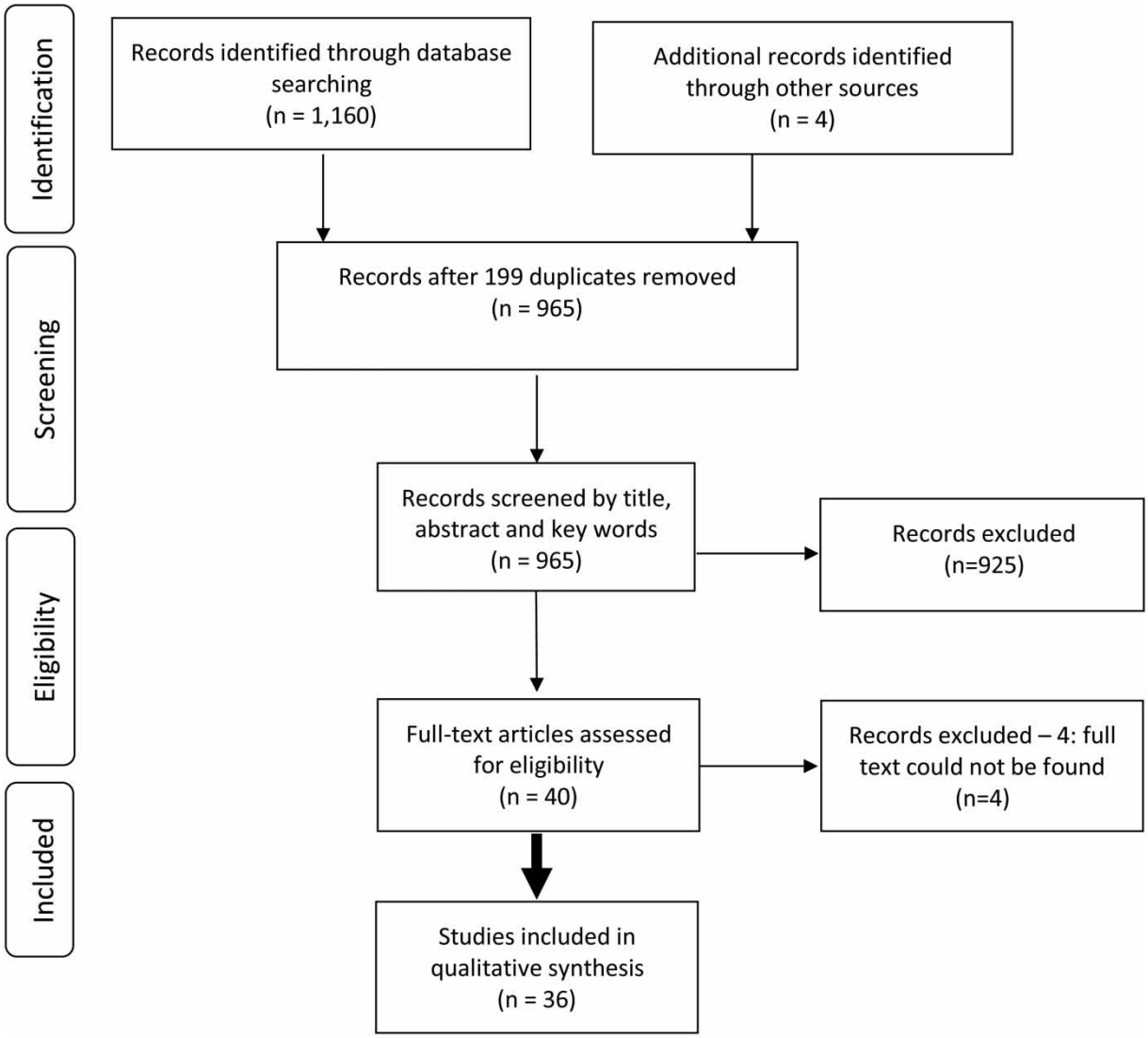


Figure 1 | PRISMA flowchart for systematic reviews showing literature search and screening process for 1,2,3-trichloropropane treatment research. Adapted from Moher *et al.* (2009). Search conducted 9 June 2020.

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

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

Table 1 | Studies included in the systematic review of treatment methods for 1,2,3-tricholoropropane

#	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.* (2003)	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)[a]	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-trichloropropane	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)[a]	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 zerovalent 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)[a]	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

(*continued*)

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

Table 1 | continued

#	Author (Publication Date)	Title	Treatment method or review
23	Mital (2014)[a]	Granular activated carbon treatment of 1,2,3-trichloropropane	GAC
24	Samin *et al.* (2014)	A *Pseudomonas putida* strain genetically engineered for 1,2,3-trichloropropane bioremediation	Bioremediation
25	Li *et al.* (2015)	Comparison of 1,2,3-trichloropropane reduction and oxidation by nanoscale zero-valent iron, zinc and activated persulfate	ZVI, ZVZ, Persulfate
26	Gong *et al.* (2017)	Combinatorial metabolic engineering of *Pseudomonas putida* KT2440 for efficient mineralization of 1,2,3-trichloropropane	Bioremediation
27	Schmitt *et al.* (2017)	Optimization and validation of enhanced biological reduction of 1,2,3-trichloropropane in groundwater	Bioremediation
28	Wang & Chu (2017)	Cometabolic biodegradation of 1,2,3-trichloropropane by propane-oxidizing bacteria	Bioremediation
29	Coyle *et al.* (2017)	Use of dilute ammonia gas for treatment of 1,2,3-trichloropropane and explosives-contaminated soils	Ammonia
30	Babcock *et al.* (2018)	Adsorption of 1,2,3-trichloropropane (TCP) to meet a MCL of 5 ppt	GAC
31	Porter & Mackey (2018)	Preparing for change: TCP overview and treatment considerations	Review
32	Kempisty *et al.* (2020)	Granular activated carbon adsorption of carcinogenic volatile organic compounds at low influent concentrations	GAC
33	Li *et al.* (2019)	In situ persulfate oxidation of 1,2,3-trichloropropane in groundwater of North China Plain	Persulfate
34	Lapeyrouse *et al.* (2019)	Remediation of chlorinated alkanes by vitamin B12 and zero-valent iron	ZVI
35	Merrill *et al.* (2019)	Development and validation of technologies for remediation of 1,2,3-trichloropropane in groundwater	Review
36	Torralba-Sanchez *et al.* (2020)	Reduction of 1,2,3-trichloropropane (TCP): pathways and mechanisms from computational chemistry calculations	ZVZ

[a]Result was identified through a source other than four-database search.

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 2017). 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

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

Table 2 | 1,2,3-Tricholoropropane distribution in the hydrosphere

Resource sampled	Continent	Country	Source information[a]	Maximum concentration (μg/L)	Study/Agency[b]
Drinking Water	Europe	Germany	German cities	0.1	Kielhorn *et al.* (2003)
	North America	Mexico	None stated	0.18	Gelover *et al.* (2000)
		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)
		China	North China Plain	None provided	Li *et al.* (2015, 2019)
		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.* (2003)
	Asia	Japan	Rivers: near Osaka	100	Yamamoto *et al.* (1997)
		Netherlands	Rivers: Rhein, Meuse, Westerscheldt, and Northern Delta	2.2	Miermans *et al.* (2000)
		Slovakia	River: Nitra	1.6	Frischenschlager *et al.* (1997)

[a]TCP source may be agricultural or industrial.
[b]From Kielhorn *et al.* (2003) and included review papers.

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 monooxygenase 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 monooxygenase include dichloropropanols (Bosma & Janssen 1998). Aerobic hydrolysis with dehalogenases produces 1,3-dichloro-2-propanol and

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

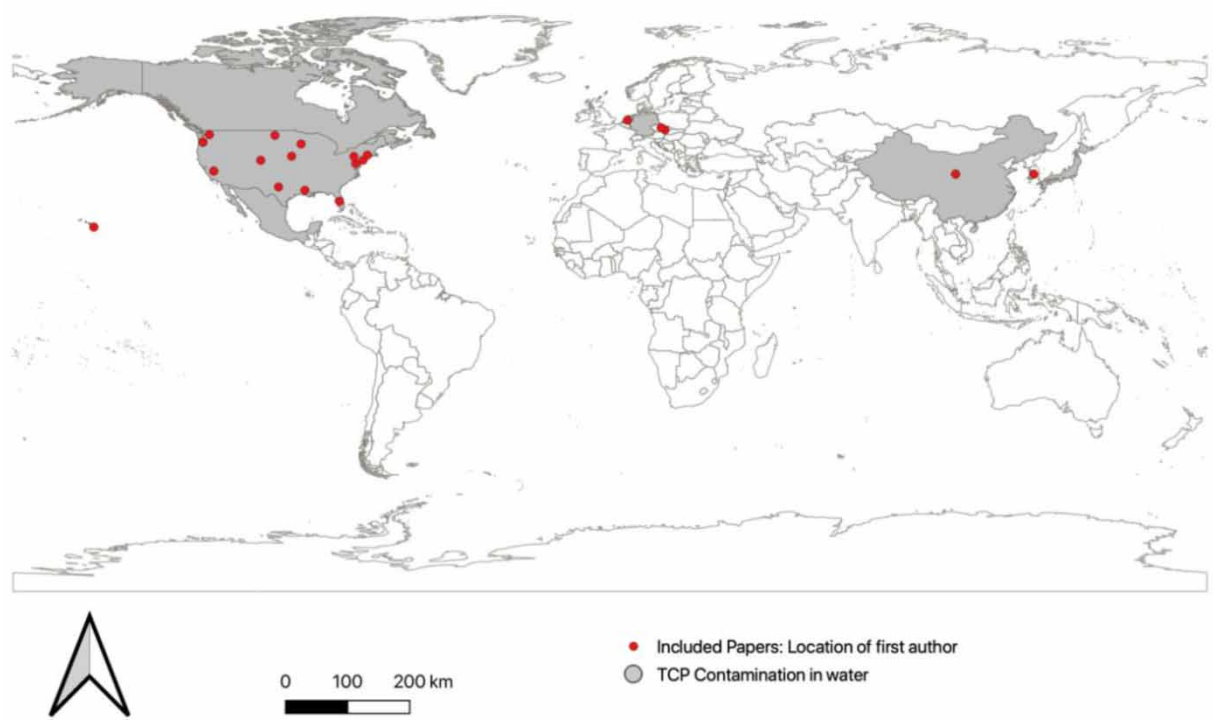


Figure 2 | 1,2,3-TCP contamination in hydrosphere and location of first author of publication.

Table 3 | Primary researcher location for 36 included papers on 1,2,3-tricholoropropane treatment

Location	Number of papers	State/Province
USA	23	Oregon (6), California (3), Hawaii (2), Pennsylvania (2), Colorado (1), Connecticut (1), Maryland (1), Minnesota (1), Nebraska (1), North Dakota (1), Florida (1), Louisiana (1), Texas (1), Washington (1)
Netherlands	5	
China	4	
Czech Republic	3	
South Korea	1	
Total	**36**	

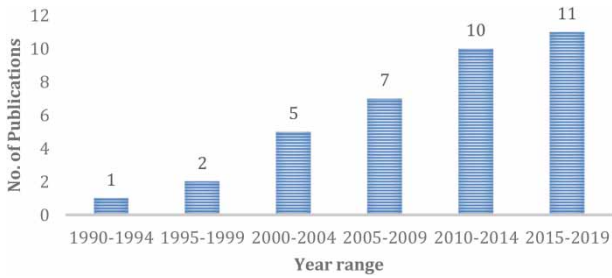


Figure 3 | Temporal trends for 36 included 1,2,3-tricholoropropane treatment papers.

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

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

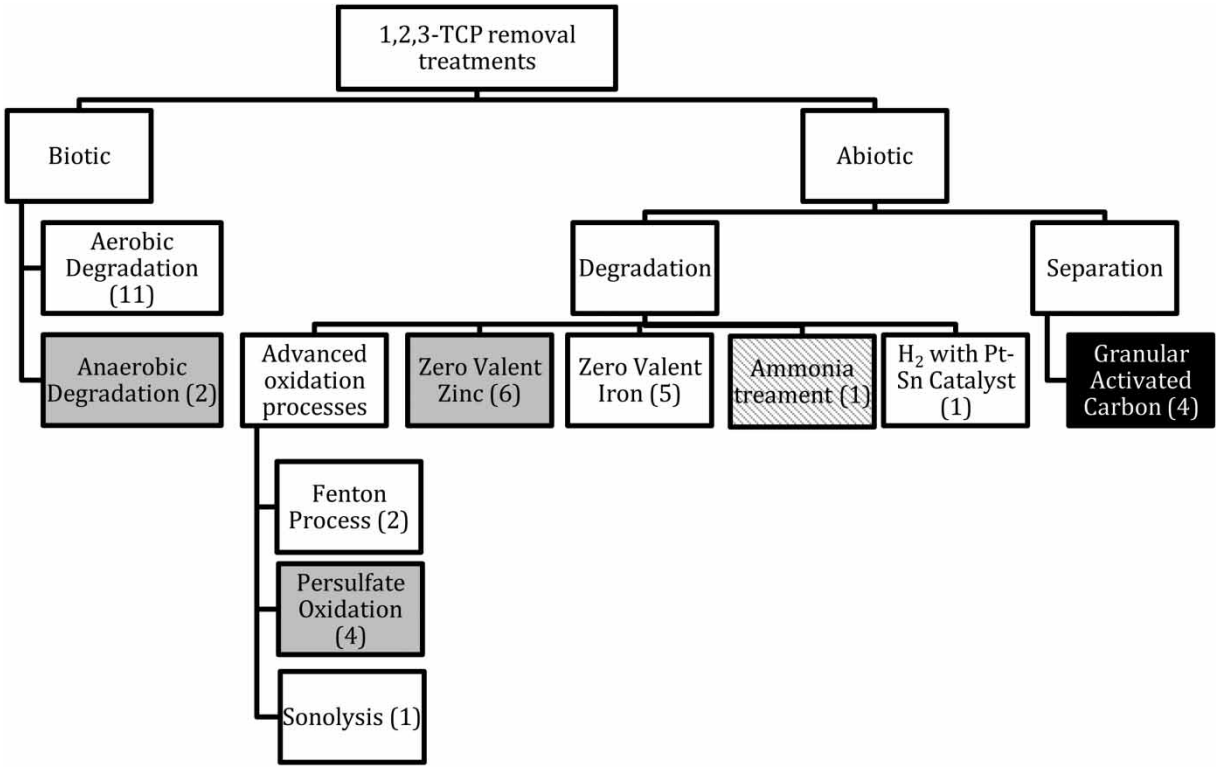


Figure 4 | Treatment method, research stage, and number of studies (parenthesis) of the research articles selected for this review. Some papers fall into multiple categories. Stage of testing is noted by shading: full-scale (black), pilot-scale (gray), bench-scale using contaminated soil (hatched), or bench-scale with TCP spiked water (white). Adapted from Miklos *et al.* (2018).

overall ability of an enzyme to convert substrate (in this case TCP) to product (Johnson & Goody 2011). K_{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).

Zerovalent iron and zinc

Eight papers investigated zerovalent metals as reductants, namely iron and zinc to treat water contaminated with TCP. Zerovalent 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

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

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 10^5 micromolar (μM). Kinetics experiments reveal that rate constants normalized for surface area (K_{SA}) were between 10^{-3} and 10^{-2} (L g^{-1} m^{-2}) (Sarathy *et al.* 2010; Tratnyek *et al.* 2010b; 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 contaminates 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

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

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 (SO_4^-), 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 Fe^{2+}-activated persulfate (Li *et al.* 2019). Li *et al.* (2019) tested the *in situ* injection of Fe^{2+}-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 Fe^{2+}-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-chloroallyamine, which is used to manufacture pesticides and pharmaceuticals.

Coyle *et al.* (2017) report TCP degradation rates ranging from 37 to 65% at 23 °C and from 89 to 94% at 62 °C. Adding dilute ammonia gas (NH_3) 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 (H_2O_2) (Babuponnusami & Muthukumar 2014). In acidic conditions, the combination of Fe^{2+}/Fe^{3+} or Zn^{2+} and H_2O_2 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/H_2O_2 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.

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

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, trichloroethylene (TCE), and TCP. Sonolysis has been used to remove volatile organic compounds from water (Mukesh *et al.* 2012). 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):

$$CH_2Cl - CHCl - CH_2Cl + 2H_2 \rightarrow CH_2 = CH - CH_3 + 3HCl$$

$$CH_2Cl - CHCl - CH_2Cl + 2H_2 \rightarrow CH_2 = CH - CH_2Cl + 2HCl$$

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 H_2 (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

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

Table 4 | Summary of 1,2,3-tricholoropropane 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 • ZVI, ZVZ, oxidation methods	• Using reductive chlorination to degrade TCP, ZVZ treatment offers more complete degradation than ZVI • TCP mineralization achieved with activated persulfate but not with mild oxidants like permanganate • Industrial-grade ZVZ degrades TCP as fast as reagent-grade
Samin & Janssen (2012)	30	• Natural abiotic degradation and biodegradation	• Full-scale TCP bioremediation is feasible if strains are found or engineered with high activity toward TCP biodegradation
Porter & Mackey (2018)	n/a	• Treatment to meet low regulatory requirements	• GAC seems to be the best available technology for TCP removal; media replacement frequencies will influence design of new treatment facilities
Merrill *et al.* (2019)	25	• Overview of the benefits and limitations of treatments • 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

for *in situ* treatment of contaminated water at low concentrations (TCP <1 mg/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 2012). However, the construction of recombinant bacterial strains with enhanced DhaA activity (Bosma *et al.* 2002) 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

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

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)[a]	Article citations	Scale of research
Bioremediation (aerobic)	11	K_{cat}/K_m = 1,050 s^{-1} 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} L m^{-2} h^{-1}	**> 10 or <8 Groundwater <7**	Sarathy *et al.* (2010)[b], Tratnyek *et al.* (2010b)[b], Salter-Blanc & Tratnyek (2011), Salter-Blanc *et al.* (2012), Hui *et al.* (2015)[b], Torralba-Sanchez *et al.* (2020)	Bench, Pilot
Zerovalent iron	5	Negligible	9.2 and 11	Vikesland *et al.* (2003), Sarathy *et al.* (2010)[b], Tratnyek *et al.* (2010b), Hui *et al.* (2015)[b], Lapeyrouse *et al.* (2019)[b]	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 M^{-1} s^{-1}	2.1–3.0	Huang *et al.* (2005), Tratnyek *et al.* (2010b), Li *et al.* (2015, 2019)	Bench, Pilot
Ammonia Treatment	1	37–65% at 23 °C and 89–94% at 62 °C	8–10	Coyle *et al.* (2017)	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

[a]If determining optimal pH was a research objective, it is listed in bold. Otherwise, listed pH values were simply stated in the methods.
[b]Both iron and zinc.

replacement 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

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

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.* 2010a, 2010b). 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

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

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 monooxygenase. *Applied Microbiology and Biotechnology* **50**, 105–112. https://doi.org/10.1007/s002530051263.

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

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/b978-1-4377-7825-0.00003-0.

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'Itri, 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., Mittermayr, C., Peck, M., Rosenberg, E. & Grasserbauer, M. 1997 The potential of gas chromatography with microwave-induced plasma atomic emission detection (GC-MIPAED) 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+kinetic&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.

Kaua'i Department of Water 2001 Puhi water system 2001, water quality report. Kaua'i Department of Water, Kaua'i, pp. 1–6.

Kearns, J. P., Bentley, M. J., Mokashi, P., Redmon, J. H. & Levine, K. 2019 Underrepresented groups in WaSH – the overlooked role of chemical toxicants in water and health. *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., Abulikemu, G., Deshpande, N. v., Rebholz, J. A., Roberts, K. & Pressman, J. G. 2020 Granular activated carbon adsorption of carcinogenic volatile organic compounds at low influent concentrations. *Journal – American Water Works Association* **1**. https://doi.org/10.1002/aws2.1128.

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., Pohlenz-Michel, C., Schmidt, S. & Mangelsdorf, I. 2003 *Concise International Chemical*

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

Assessment Document 56 – 1,2,3-Trichloropropane. World Health Organization, Geneva. https://doi.org/10.1515/ci.2003.25.1.21b. 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. 2003 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/es025965s

Kurumbang, N. P., Dvorak, P., Bendl, J., Brezovsky, J., Prokop, Z. & Damborsky, 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. & Wathen, 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://hydrologie.org/redbooks/a188/iahs_188_0171.pdf.

Lapeyrouse, N., Liu, 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 DadB 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 Sonochemistry* **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. 2019 Development and validation of technologies for remediation of 1,2,3-trichloropropane 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**, 118–131. 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/cc0e327c51534acc8ae8922b9b3218bc/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., Vévodová, 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/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., Otyepka, 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*

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

Water Works Association **110**, 31–35. https://doi.org/10.1002/awwa.1059.

Reemtsma, T., Berger, U., Arp, H. P. H., Gallard, 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. *Chemistry Central Journal* **8**. https://doi.org/10.1016/j.marpolbul.2013.01.035

Schmitt, M., Varadhan, S., Dworatzek, S., Webb, J. & Suchomel, E. 2017 Optimization and validation of enhanced 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) 2017 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) 2018 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/123tcp_utility_training.pdf (accessed 18 December 2020).

Torralba-Sanchez, 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. 2010b 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/development-agenda/ (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/remedytech/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**,

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest

1169–1171. https://doi.org/10.1128/aem.56.4.1169-1171.1990.

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/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/acs-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., Kakutan, i 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

Downloaded from http://iwaponline.com/washdev/article-pdf/11/4/515/913494/washdev0110515.pdf
by guest