United States Department of Agriculture
Agricultural Marketing Service | National Organic Program

Document Cover Sheet

Document Type:

☐ **National List Petition or Petition Update**

A petition is a request to amend the USDA National Organic Program's National List of Allowed and Prohibited Substances (National List).

www.ams.usda.gov/rules-regulations/organic/national-list

Any person may submit a petition to have a substance evaluated by the National Organic Standards Board (NOSB) [7 CFR 205.607(a)].

www.ams.usda.gov/rules-regulations/organic/nosb

National List Petition Guidelines for submitting a petition are available on the AMS website at How to File a Petition.

www.ams.usda.gov/rules-regulations/organic/national-list/filing-petition

AMS posts completed petitions online for public access on the NOP Petitioned Substances Index

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☒ **Technical Report**

A technical report is developed in response to a petition to amend the National List. Reports are also developed to assist in the review of substances that are already on the National List. Technical reports are completed by third-party contractors and AMS posts completed technical reports online for public access on the NOP Petitioned Substances Index. Contractor names and dates completed are available in the report.

www.ams.usda.gov/rules-regulations/organic/petitioned-substances

Read more about the technical report process in section **H. SUBSTANCE/MATERIALS REVIEW PROCESS** in the NOSB Policy & Procedures Manual posted on the AMS website.

www.ams.usda.gov/sites/default/files/media/NOSB-PolicyManual.pdf

www.ams.usda.gov/rules-regulations/organic/nosb

Chlorine Materials

Crops, Livestock, and Handling/Processing

Chemical Names and Identification

Chemical Names

Calcium hypochlorite, chlorine dioxide, hypochlorous acid, potassium hypochlorite, acidified sodium chlorite, sodium hypochlorite (see *Table 1* for other names, trade names, and codes).

Table 1: Identification of chlorine materials *(EPA, 2025c; U.S. NLM, 2025b). Chemical, trade, other names, and codes used to describe various chlorine materials. The table also includes the number of pesticide products that use the various substances as active ingredients that are currently registered with EPA as of November 8, 2025 (EPA, 2025c), shown in parentheses under the chemical names.*

Chemical name (number of EPA registered products)	Other names	Trade names	Codes
Calcium hypochlorite (799)	Bleaching powder; calcium dihypochlorite; chlorine peroxide; chloroperoxide; hypochlorous acid, calcium salt.	Aqua Doctor; Aquafit; Bioguard CLC; Buccaneer; Cal Hypo; ECR Aquachlor; Hy-Chlor; Lo Bax; Losantin; Pittchlor; Plant Pro; Pool Shock.	CAS: 7778-54-3 EPA PC: 014701 EINECS: 231-908-7 UN: 1748
Chlorine dioxide (66)	Chlorine oxide; chlorine peroxide; chloryl radical.	Alcide; Anthium Dioxcide; Aqua Nova; Duzzit; Envirocon; FruitGard®; Oxine; Purite; Sanicide; Z-Series®.	CAS: 10049-04-4 EPA PC: 020503 EINECS: 233-162-8 CHEBI: 29415 EU: E926
Hypochlorous acid (227)	Chloranol	Agrowlyte; Annihilyte; BacteriaNex; BioBlast; Briotech; Chemichlon G; Cousteau; FloraFresh; Hyposhield; Klor; Pathonex; Pureox; UltraLyte; Viracyn.	CAS: 7790-92-3 EPA PC: 129054 EINECS: 232-232-5 CHEBI: 24757
Potassium hypochlorite (1)	Hypochlorous acid, potassium salt; Javel water; potassium chloride oxide; potassium oxychloride.	Enviro Klor™	CAS: 7778-66-7 EPA PC: 129053 EINECS: 231-909-2
Sodium chlorite (261)	Chlorite sodium; chlorous acid, sodium salt.	Agriwater; Aquaprove; DrewChlor; Drubber; Envirochlorite; Fit Fresh Produce Wash; Purecide; Sabrechlor; Textone®; Udder Care Barrier Part B; Udderstar.	CAS: 7758-19-2 EPA PC: 020502 EINECS: 231-836-6 UN: 1496 CHEBI: 78667
Sodium hypochlorite (1,511)	Bleach; Dakin's solution; hypochlorous acid, sodium salt.	AgClor; AgriClor; Agri-Clor; Antiformin; B-K; ChemClor; Clorox®; Dairychlor; Greenhouse Aid; Hypochlor; Perchloron, Purin B; Superchlor; Zep Control.	CAS: 7681-52-9 EPA PC: 014703 EINECS: 231-668-3 UN: 1791 CHEBI: 32146

Information Requested

This limited scope technical report provides updated information to the National Organic Standards Board (NOSB) to support their review of chlorine materials in the crops, livestock, and handling scopes with sunset dates in 2028.

The NOSB requested a response to *Evaluation Question #7* from the technical report template. Evaluation Question #7 is the same in both the Crops/Livestock technical report template and the Handling/Processing template.

The NOSB also requested responses to *Evaluation Questions #3, #4, #6, and #9* from the Crops/Livestock technical report template. To provide a more complete discussion of alternatives, this technical report also includes a response to *Evaluation Question #10* (alternative practices).

The NOSB also requested responses to the following Crops/Livestock Focus Questions:

- *Focus Question #1*: Do chlorine concentrations that are within the maximum residual disinfectant impart significant sanitizing properties to water?
- *Focus Question #2*: Do the higher initial application rates indicated in the 2024 technical report increase the likelihood of formation of carcinogenic trihalomethanes when chlorine materials interact with organic matter? Please expand on this and add any new findings.
- *Focus Question #3a*: How exactly are the various chlorine materials used in sanitizing irrigation lines, animal drinking water, and milk lines, etc. to meet OFPA [NOP] regulations?

- *Focus Question #3b*: Are they used at any point at concentrations above the 4 ppm limit?
- A brief explanation on the differences in chemical activity among chlorite, chlorate, chlorine dioxide and chloride compounds. See *Action of the Substance*.
- Additional information on the conditions that favor the formation of carcinogenic toxic materials when chlorine materials interact with organic materials will be very useful. In answer to this, please see *Disinfection by-products* in Evaluation Question #3, *Disinfection by-product toxicity in humans* and *Disinfection by-product toxicity in animals* in Evaluation Question #4, and *Focus Question #2*.

This technical report also provides background and characterization information that contextualize the responses.

Background

When Does Water Need To Be Treated In Order To Be Used?

Congress passed the Food Safety Modernization Act (FSMA) (Public Law 111-353, January 4, 2011) in 2010, and it was signed into law in 2011. This law directed the FDA to amend regulations related to food production. FSMA is designed to prevent foodborne illnesses through appropriate controls (Thatte, 2019). Under current FDA regulations, crop producers and post-harvest handlers in the United States are subject to complex rules related to water use. For example, the FDA requires that crop producers growing crops usually eaten raw (referred to by FDA as "covered produce") prepare an agricultural water assessment at least annually (21 CFR 112.43). *E. coli* is the primary species tested for the water assessment as an indicator for fecal contamination, but producers and handlers may use another scientifically valid indicator organism, index organism, or analyte [21 CFR 112.43(d)(2)]. Other bacteria tested may include *Salmonella* spp. or *Listeria* spp. (ALBA & NCAT, 2016).

FDA regulations specify that untreated *surface* water is not allowed for irrigating sprouts, used during harvest activities when it will contact produce, used on food contact surfaces, or for handwashing during harvest [21 CFR 112.44(a)]. However, untreated *ground* water is allowed for these purposes if it meets certain testing requirements [21 CFR 112.44(b)]. Water must not contain detectable *Escherichia coli* bacteria, using a specific EPA-approved method of analysis (ALBA & NCAT, 2016).

If untreated water is used for an acceptable purpose (*e.g.,* prior to harvest), but poses a hazard, FDA regulations specify that the operation must immediately discontinue use [21 CFR 112.45(a)] or implement mitigation measures [21 CFR 112.45(b)]. Chemical treatment is not the only mitigation option and is not always practical, but it is a viable option [21 CFR 112.45(b)(v)]. Chlorine products are not specifically mentioned as a treatment in the FDA regulations; however, the FDA allows any EPA-registered antimicrobial pesticide or other suitable methods that are effective to treat agricultural water [21 CFR 112.46(a)]. The FDA also specifies that operators need to monitor treated water to ensure the water meets safety and quality requirements [21 CFR 112.46(c)].

A variety of laws and regulations apply to the practical use of water and therefore different regulatory agencies are involved with oversight. The EPA and the FDA established a Memorandum of Understanding to help clarify who is responsible for water in different circumstances (FDA & EPA, 2017). For example, the Safe Drinking Water Act (SDWA) (Public Law 93-523, December 16, 1974) passed by Congress gave EPA the authority to establish standards for public water supplies. Congress directed the EPA to establish standards for maximum contaminant levels in drinking water to protect public health and safety. The SDWA regulations are published at 40 CFR part 141. They do not directly apply to private wells under certain conditions, bottled water, or water used as an ingredient in food.

The Federal Food, Drug, and Cosmetic Act (FFDCA) (21 U.S.C. 301-392) gives the FDA authority to regulate food and food additives (FDA & EPA, 2017). FDA regulations require that any water that contacts food, food-contact surfaces, or food-packaging materials must be safe and of adequate sanitary quality. (21 CFR 117.37). The FDA also regulates bottled drinking water (21 CFR 129).

Water used to process meat and poultry products are subject to the Meat Inspection Act (Public Law 59-382, June 30, 1906) and the Poultry Products Inspection Act (PL 85-172, August 28, 1957). The FSIS regulations require meat and poultry establishments under their authority to have a supply of running water that complies with the EPA's National Primary Drinking Water standard [9 CFR 416(g)(1)]. Water used to clean eggs is subject to the Egg Products Inspection Act (91-597, December 29, 1970) regulations (9 CFR 590).

Sanitizers VS. Disinfectants

The terms "sanitizer" and "disinfectant" are used interchangeably in the literature, but some agencies have more precise definitions that distinguish the two terms to describe relative antimicrobial effectiveness. The choice of term varies based on different scopes, food products, uses, and applications, and the materials and methods used to control various target organisms. Further complicating the use of these terms, biomedical and veterinary professionals may use the terms in different ways from food safety professionals. In general, this technical report uses the terms as they were used in the relevant cited sources. In a few cases, we offer clarification of terms to fit within the specific context of the section. A glossary of terms and list of acronyms related to sanitizers, disinfectants, and the use of chlorine are included in *Table 9: Glossary of terms* in *Appendix A*.

The FDA makes the following distinction between sanitizers and disinfectants with respect to food safety applications in a non-regulatory publication (FDA, 2011). Sanitizers and disinfectants both kill target undesirable microorganisms in food. These fall into three categories (FDA, 2011):

1. Sanitizers of non-food contact surfaces that reduce target organisms by 3 logs;
2. Sanitizing rinses of previously cleaned food contact surfaces that reduce target organisms by 5 logs; and
3. Disinfectants that eliminate undesirable organisms from inanimate objects.

The FDA does not measure disinfectant performance by log reduction as it does sanitizers and sanitizing rinses (FDA, 2011).

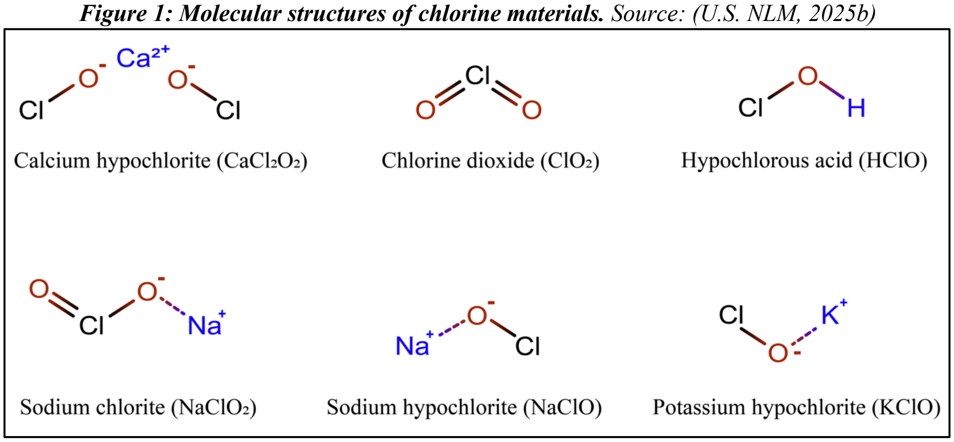
Characterization

Specific Uses of the Substance

Thousands of chemicals are made with chlorine as a precursor, many of which are pesticides (American Chemistry Council, 2025; Bommaraju et al., 2002; Schmittinger et al., 2011). A small number of these pesticide active ingredients are permitted by the USDA organic regulations with annotations that limit their specific uses (NOP, 2024b). Many chlorine products are EPA registered pesticides. See *Table 1* for counts of EPA registered pesticides that contain active ingredients allowed for organic production and handling.

One of the most common chlorine materials is sodium hypochlorite (see *Figure 1*, NaClO). Sodium hypochlorite in aqueous solution is generally referred to as "bleach" (Gagliardi, 2025). Other ingredients in bleach products include stabilizers and pH adjusters like sodium chloride (NaCl), sodium carbonate ($NaCO_3$), and sodium hydroxide (NaOH). Sodium chlorate ($NaClO_3$) is present as an intermediate molecule from the processing of salt water to bleach (Gagliardi, 2025).

Figure 1: Molecular structures of chlorine materials. *Source: (U.S. NLM, 2025b)*



Chlorine is a commonly used disinfectant and sanitizer because of its availability and affordability (Bihn & Reiners, 2018). Chlorine materials are used for a variety of purposes and at different rates in organic production (see *Table 2*). For example, the use rate in irrigation water system treatment is a continuous 1-2 ppm (EnviroTech Chemical Services, 2019). Application rates on seeds for sprouting can be as high as 20,000 ppm or a 2% solution (FDA, 2023b).

Table 2: A selection of chlorine materials used in organic production and handling. *The table provides examples of the different uses of chlorine materials on organic operations. Due to the number of possible products, formulations, and applications, the recommended or labeled rates included in the table are examples based on sodium hypochlorite products. Post-application procedures are examples that could be used to meet the annotation on the National List and NOP 5026 The Use of Chlorine Materials in Organic Production and Handling (NOP, 2024b).*

Scope and use	Materials listed for use	Example recommended/labeled rates of available chlorine	Post-application procedure	Sources
Crops				
Irrigation water system treatment	ClO_2; KOCl; NaOCl	1-2 ppm (continuous) 20 ppm (shock)	None needed at levels of 4 ppm or less. Flush with fresh water after shock treatment.	(Clorox, 2021; EnviroTech Chemical Services, 2017; Morris, 2023)
Wastewater treatment	ClO_2; NaOCl	5-20 ppm	Dechlorination with sulfur dioxide, sodium bisulfite, or sodium metabisulfite.	(EPA, 1999, 2012)
Seed treatment for potatoes, rice, wheat, and other crops grown in soil	NaOCl; $CaCl_2O_2$; HOCl; ClO_2	1,500-20,000 ppm	Treatment is followed by immediate rinsing with potable water that does not exceed the maximum residual disinfectant level (MRDL) under the Safe Drinking Water Act (SDWA).	(Alexander Chemical Co., 2020; Clorox, 2019a; Janish, 2025; NOP, 2013a)
Seed treatment for sprouts	$CaCl_2O_2$; NaOCl	19,000-20,000 ppm	None.	(Axiall, 2018; FDA, 2023b)
Farm tools, equipment, and machinery	NaOCl; $CaCl_2O_2$; HOCl; ClO_2	8,500-10,000 ppm (0.85-1.00%)	None.	(Clorox, 2019a)
Livestock				
Barns, facilities, feeders	NaOCl; $CaCl_2O_2$; HOCl; ClO_2	200-5,000+ ppm	Clean, clear cold water rinse.	(Clorox, 2021; NYSCHAP, 2025b)
Livestock drinking water	NaOCl	2-5 ppm	Water in direct contact with livestock, including drinking water, is limited to the SDWA limits by NOP Guidance.	(Clorox, 2019a; NOP, 2024b)
Equipment in contact with raw fluid milk	NaOCl; $CaCl_2O_2$; HOCl; ClO_2	200 ppm	Rinse with an alkali or acid solution. Rinse with hot water (>170 °F for 5+ minutes). Completely drain the equipment before milking.	(Clorox, 2021; Jones, 2009; Sigurdson et al., 2004)
Shell egg wash	NaOCl; $CaCl_2O_2$; HOCl; ClO_2	200 ppm	Follow with a potable water rinse. Air dry as quickly as possible.	(Clorox, 2019a; Negrete, 2014)
Teat dip	$NaClO_2$	5,000 – 10,000 ppm (0.5-1.0% active ingredient before activation)	Pre-milking: Wipe teats dry with a single service towel. Post-milking: Allow to air dry.	(Ecolab, 2021; U.S. NLM, 2025a)
Bee hives and other honey production uses	NaOCl; ClO_2	1 ppm	Air dry completely before reintroducing bees.	(Aries Chemical, 2013; Mahdi et al., 2022)
Handling				
Food contact surfaces, equipment and facilities	$NaClO_2$; NaOCl; $CaCl_2O_2$; HOCl; ClO_2	150-200 ppm	None.	(Clorox, 2019a)
Fruit and vegetable cooling and wash water	NaOCl; $CaCl_2O_2$; HOCl; ClO_2	25-600 ppm 25-400 ppm (Calcium hydroxide)	Rinse with potable water.	(Axiall, 2018; Clorox, 2019a; Suslow, 1997)
Poultry chiller water	NaOCl; $CaCl_2O_2$; HOCl; ClO_2	25-50 ppm	Lower rates in contact with poultry carcasses may not be permitted by FSIS regulations.	(Clorox, 2019a)
Carcass disinfection	NaOCl; $CaCl_2O_2$; HOCl; ClO_2	5-50 ppm	Processing water cannot be reused or recirculated.	(Clorox, 2019a)

Crops

Disinfecting seeds

Organic producers use chlorine to treat seeds used for edible sprout production. Researchers reported that before the NOP rule codified the USDA organic regulations, some organic/low-input farmers used chlorine solutions to treat seeds for seedborne pathogens prior to planting (Smith, 1994). Chlorine treatment is also used to treat seeds and seed potatoes (Clorox, 2019a; Janish, 2025; Miller & Lewis Ivey, 2005). According to NOP 5029 *Guidance: Seeds, Annual Seedlings, and Planting Stock in Organic Crop Production*, organic producers are permitted to use chlorine materials to treat seeds on-farm, provided the treatment is followed by immediate rinsing with potable water that does not exceed the maximum residual disinfectant level (MRDL) under the Safe Drinking Water Act (SDWA) (NOP, 2013a). Seeds treated with chlorine will kill pathogens on the seed surface, but not those inside the seed (Miller & Lewis Ivey, 2005).

Cleaning irrigation equipment

Organic producers also use chlorine compounds as an algicide and antimicrobial in irrigation equipment (Migliaccio et al., 2009; Morris, 2023; Morris & Schwankl, 2023). Drip irrigation can be clogged by physical, chemical, or biological blockages (Bucks et al., 1979; Nakayama & Bucks, 1991). Physical clogging is mostly caused by suspended solids in the drip irrigation line in the form of silt, clay, and other sediments, including organic matter from decaying plants and other organisms (Nakayama & Bucks, 1991). Chlorination addresses only the biological clogging associated with algae and biofilms produced by bacteria (slime) and does not remove physical or chemical deposits (Nakayama & Bucks, 1991). Control of microbial slime and algae can alleviate the quantity of suspended particles that stick to the slime and agglomerate in the lines and emitters (Nakayama & Bucks, 1991).

Various organisms occur naturally in both ground- and surface-water that are transported in irrigation water (Maynard & Hochmuth, 1997; Migliaccio et al., 2009). Treated wastewater is particularly prone to the growth of algae, protozoa, and other organisms that clog drip irrigation systems (Raudales et al., 2014). Algae and various microorganisms form biofilms that clog emitters, reduce irrigation efficiency, and thereby reduce plant growth (Dehghanisanij et al., 2005; Raudales et al., 2014). In some cases, producers use filtered water in irrigation systems to reduce the microorganism load, but filtration alone will not effectively remove microorganisms (Migliaccio et al., 2009).

Chemical clogging results from dissolved substances in water like calcium carbonate ($CaCO_3$, known as lime or limestone) and calcium sulfate ($CaSO_4 \times 2H_2O$, known as gypsum) (Morris, 2023). In some cases, chlorination itself can cause chemical clogging (Migliaccio et al., 2009; Nakayama & Bucks, 1991). For example, chlorine can cause iron to precipitate in the water, which can also clog emitters (Nakayama & Bucks, 1991). Calcium hypochlorite is more likely to precipitate chemicals that can clog emitters as well in some circumstances (Migliaccio et al., 2009). Unless regular maintenance addresses all contributors to drip irrigation system clogging, chlorination will be ineffective (Bucks et al., 1979; Migliaccio et al., 2009; Morris, 2023; Nakayama & Bucks, 1991).

Treating irrigation water

Non-potable wastewater treated with antimicrobial pesticides is a significant source of irrigation water applied to agricultural crops worldwide (A. Singh, 2021; Song et al., 2017). Urban wastewater is commonly treated with chlorine to reduce foodborne pathogens before it is recycled and released to irrigate food crops grown for human consumption (Jongman & Korsten, 2017; Lonigro et al., 2017; López-Gálvez et al., 2017, 2017; Murrell et al., 2021; Raudales et al., 2014; A. Singh, 2021). Most wastewater treatment systems maintain chlorine levels in the range of 5-20 ppm available chlorine (EPA, 1999). Sewage sludge is prohibited for use in organic production [7 CFR 205.105(g)].

Disinfecting tools and other equipment

Organic producers use chlorinated solutions to disinfect tools, equipment, greenhouses, and other facilities on organic farms (Coleman, 2012; Gauthier et al., 2020; Smith, 1994). Organic producers also use chlorine to disinfect reused containers for greenhouse production (Coleman, 2012). Tractor tires and implements may be sanitized with chlorine bleach to prevent movement of nematodes between fields (McCulloch et al., 2023). Potato storage bins may be disinfected with different chlorine products to eliminate spores associated with various post-harvest diseases (Olsen & Nolte, 2011).

Livestock

Disinfecting facilities and equipment

Chlorine is a common disinfectant of livestock facilities and equipment (Darre, 2014; Jones, 2009; NYSCHAP, 2025a). Producers also use chlorine materials to disinfect dairy barns (NYSCHAP, 2025a). Chlorine dioxide is used at concentrations of 25-50 ppm over a two minute contact period to sanitize calf feeding equipment, and at a concentration of 250-500 ppm with 5-10 minutes of contact time to disinfect facilities and calf pens (Sockett, 2021).

Poultry houses are disinfected with chlorine to control *Salmonella enteritidis, E. coli*, and other foodborne pathogens (Darre, 2014). The recommended rate is one gallon of diluted disinfectant per 150-200 square feet of surface area. The recommended dilution rate to clean waterers and feeders is 200 ppm of chlorine (Darre, 2014).

Disinfecting livestock drinking water

Drinking water used for livestock may be treated with chlorine to control bacteria and parasites (Clorox, 2019a). The guidance document, NOP 5026 *The Use of Chlorine Materials in Organic Production and Handling*, cites drinking water as an example of direct contact with animals, and specifies that the water should not exceed the MRDL under the SDWA (NOP, 2024b). Chlorine sanitizers have long been used to disinfect milking equipment (Breed, 1922; Cousins, 1977; Marshall, 1985; Prucha, 1928).

Disinfecting dairy equipment

Most dairy farms—including most organic dairy farms—in the U.S. are subject to the U.S. FDA's Pasteurized Milk Ordinance (PMO). The PMO establishes mandatory requirements for dairy producers to follow if they sell to a pool that ships raw milk used to make products sold in interstate commerce (FDA, 2023a). The PMO establishes minimum requirements to clean, disinfect, and sanitize dairy facilities and equipment for raw milk to be sold for interstate commercial use. These requirements establish effective levels of chlorine required for control of pathogens that might enter the milk supply. They also set limits on free available chlorine contamination of milk. State, local, or tribal jurisdictions have some discretionary authority about specific requirements (FDA, 2023a).

Most dairy farms have clean-in-place (CIP) systems for delivering the sanitizers (Jones, 2009). Disinfection by-products in milk and dairy products resulting from inadequate intervening events are addressed in Evaluation Question #3. Cleaning and sanitizing milking equipment is necessary to protect the safety and quality of raw milk from bacterial contamination (Jones, 2009; NYSCHAP, 2025a; Sigurdson et al., 2004). Extension publications and dairy quality programs recommend that milking machines be cleaned twice daily (Jones, 2009; NYSCHAP, 2025a). While each dairy farm will have its own cleaning procedure and the order may vary, to quote one dairy industry guide, "cleaning consists of a pre-rinse, washing, and a post-rinse, followed by sanitizing or disinfecting" (Sigurdson et al., 2004):

1. Pre-rinse: to remove the milk "soil"
2. Wash: to remove any remaining visible soils
3. Post-rinse: to clear the equipment of the detergents and soils from washing
4. Sanitize/disinfect: to kill pathogenic or spoilage microorganisms

According to Jones (2009), the pre-rinse step should use water that is 100-110 °F immediately after milking to prevent milk soil from drying on the equipment. The New York State Cattle Health Assurance Program states that each cleaning should involve an acid or alkali cleaning compound (NYSCHAP, 2025a). The washing step may involve a chlorinated alkali cleaner (Jones, 2009; Sigurdson et al., 2004). The post-rinse is sometimes a two-step process involving an acid (Jones, 2009).

One author states that four interrelated variables make the cleaning program effective (Sigurdson et al., 2004):

1. The concentration of the cleaning agent;
2. The temperature of the water;
3. The time required to clean the dairy equipment; and
4. The force required to remove milk soil and microorganisms—both mechanized and manual.

Hot water applied as a sanitizer needs to be maintained at 170 °F for five minutes to meet regulatory and industry standards (Sigurdson et al., 2004). Pipelines and bulk milk tanks are commonly sanitized before milking (Jones, 2009).

Early users of chlorine materials recognized that sanitizer residues may be a concern, and at least one extension circular recommended rinsing with hot water following application, before the machines and equipment received any fluid raw milk (Prucha, 1928). The PMO continues to limit residual chlorine and recognizes procedures for de-chlorination at its 100th anniversary (FDA, 2023a).

<u>*Disinfecting teats on dairy animals*</u>

At least 137 microbial species, subspecies, and serovars (similar to variety) have been isolated from milk and implicated in causing an udder infection known as mastitis (National Mastitis Council, 2017). The most common are the bacteria of the genera *Streptococcus* and *Staphylococcus* (National Mastitis Council, 2017). Teat disinfectants and dips are important tools to use before and after milking to prevent mastitis (Enger et al., 2016). Acidified sodium chlorite is used as a teat dip both pre- and post-milking (Ecolab, 2012; NOP, 2013b).

While they are considered drugs, the FDA states that teat dips and udder washes can be marketed without New Animal Drug Application (NADA) approval (FDA, 1995). Because of this, the FDA does not list acidified sodium chlorite or other teat dips in the *Approved Animal Drug Products* (Green Book) publication.

An advance search of the National Library of Medicine's DailyMed database for "sodium chlorite teat dip" on November 9, 2025 found 85 over-the-counter teat dip products that listed sodium chlorite as the active ingredient (U.S. NLM, 2025a). The concentration of active ingredients reviewed from this search result generally ranged from 0.5% to 1.0% active sodium chlorite (U.S. NLM, 2025a). All product instructions reviewed required mixing with an acidic solution containing citric acid or lactic acid as the activator used to convert sodium chlorite into chlorine dioxide (U.S. NLM, 2025a). Formulations generally followed a 1:1 ratio of base to activator (U.S. NLM, 2025a). The release of chlorine dioxide and formation of chlorous acid from the acidification of sodium chlorite depends on pH and the concentration of sodium chlorite (JECFA, 2008). Disassociation of sodium chlorite to chlorous acid is about 31% at pH 2.3, 10% at pH 2.9, and 6% at pH 3.2 (JECFA, 2008).

<u>*Sanitizing eggs*</u>

Chlorine products are used to clean and sanitize organic eggs (NOP, 2014). USDA Food Safety and Inspection Service (FSIS) regulations require that eggs must be clean prior to packaging, breaking, or pasteurizing [9 CFR 590.516(a)]. If a sanitizer is used, it must be used in accordance with FDA requirements for the intended use [9 CFR 590.516(a)]. Unless FSIS provides a waiver for an approved alternative with equivalent efficacy, shell eggs are spray rinsed with potable water containing an approved chlorine sanitizer of 100-200 ppm of available chlorine (NOP, 2014). The FSIS regulations further specify that the eggs must be sufficiently dry before breaking [9 CFR 590.516(b)]. The FSIS regulations and NOP Policy Memo 14-2 *Chlorine Use in Egg Breaking Facilities* (NOP, 2014) do not provide for or require a rinse with potable water after chlorine use.

<u>*Disinfecting beehives and apiculture equipment*</u>

Apiculturists use chlorine products to disinfect beehives and other beekeeping equipment (Aries Chemical, 2013). American foulbrood (*Paenibacillus larvae*) is a major disease of honeybees (Mahdi et al., 2022). The disease is transmitted when nurse bees give food infected with the bacterial spores of *P. larvae* to larvae (Wood, 2022). The activated spores infect the intestines of larvae, resulting in the developing bee's death (Wood, 2022). The decaying brood desiccates into hard scales, tightly adhering to the walls of the hive's cells (Genersch et al., 2006). The infection is further spread by worker bees cleaning the cells and moving the scales infected with the spores into other parts of the hive (Wood, 2022). In one study, researchers treated wood, steel, and glass infected with American foulbrood spores under laboratory conditions with chlorine dioxide at different concentrations for various durations (Mahdi et al., 2022). Treatment at levels above 0.2 ppm and exposure times of over 2 hours were effective in inactivating all *P. larvae* spores on every surface tested (Mahdi et al., 2022).

The advantages for beekeepers of chlorine and chlorine compounds are that they are (Bojanic Rasovic, 2021):

- inexpensive
- fast acting
- easily available

The disadvantages of chlorine disinfectants for beekeepers are that they (Bojanic Rasovic, 2021):

- are corrosive to metals
- are inactivated by organic matter
- can be irritating to skin and mucous membranes
- should be used in well-ventilated rooms
- have a shortened shelf life after dilution

Handling

Disinfecting fresh produce

Processors may use wash water treated with chlorine to disinfect fresh commodities on-farm at harvest, post-harvest, or by a packing house or other off-farm post-harvest handling facility (Long et al., 2024; Suslow, 1997). Fresh produce is hydrocooled at a temperature close to 0 °C to remove field heat from perishable fruits and vegetables, and the cooling water is regularly treated with 100-150 ppm of available chlorine to control organisms (Elansari et al., 2019). Water is often recirculated, and such systems will treat the water at a rate of 50-100 ppm to reduce bacterial buildup (Elansari et al., 2019; Suslow, 1997). Higher rates may be needed with some underground crops like potatoes (Suslow, 1997). Dirty produce or high organic matter content in the water will also require greater doses of available chlorine (Suslow, 1997).

Sanitizing food contact surfaces

Chlorine products are commonly used to sanitize food contact surfaces and equipment (Bihn & Reiners, 2018; Marriott et al., 2018; Park & Kang, 2017; Troller, 1993). Equipment treated at available chlorine levels below 200 ppm generally does not need to be rinsed before being used to handle food (Marriott et al., 2018). Product labels include instructions on the steps needed to prevent residual contamination from food contact surfaces, and organic producers are required to use pesticides according to the label (NOP, 2024b). The NOP states in the guidance document NOP 5026 *The Use of Chlorine Materials in Organic Production and Handling*, "chlorine materials may be used up to maximum-labeled rates for disinfecting and sanitizing food contact surfaces. Rinsing is not required unless mandated by the label use directions" (NOP, 2024b).

Some applications may require a clean water rinse after chlorination, such as when a higher concentration of chlorine is used (Lynch, 2020), while others may not. If a product does not require a water rinse, then the sanitized food contact surface should air dry (Lynch, 2020).

Chlorine is the most effective bacterial disinfectant for most food contact surfaces (Gallandat et al., 2021). It also has the advantage of being relatively inexpensive compared to most alternatives and it is widely used (Meireles et al., 2016). Hypochlorous acid reportedly kills a broader range of microorganisms than any other approved sanitizer (Wirtanen & Salo, 2003). Effective alternatives will often incur a higher cost, may require investment in new equipment, and in many cases will be less effective (Meireles et al., 2016).

Treating poultry chill water

Poultry processors use chlorine to treat poultry chiller water and to sanitize carcasses following evisceration (Najjar & Meng, 2009; Tsai et al., 1992). Organic meat and poultry processors may treat slaughtered animal carcasses with chlorine at the levels approved by FDA or EPA for such purposes (NOP, 2024b). In the guidance NOP 5026, the NOP stipulates that food treated with chlorinated water must be rinsed with potable water that does not exceed the MRDL of the SDWA immediately following use and processors must monitor that use (NOP, 2024b).

Chlorine is by far most common choice of U.S. poultry processors for carcass disinfection because of its efficacy, availability, and low cost (Russell, 2007; Tsai et al., 1992). The European Union has banned chlorine washing or spin chilling of poultry in chlorinated water since at least 1997 (Echols, 1998; James et al., 2006). Dry air chilling is the preferred method among European poultry processors (James et al., 2006).

Approved Legal Uses of the Substance

In addition to USDA's organic regulations, chlorine materials are regulated by the U.S. Food and Drug Administration (FDA), the U.S. Environmental Protection Agency (EPA), and USDA's Food Safety and Inspection Service (FSIS).

Crops

Organic regulations

Chlorine materials are included on the National List of Allowed and Prohibited Substances (hereafter referred to as the "National List") as synthetic substances allowed for organic crop production at 7 CFR 205.601(a)(2). The annotation for chlorine materials specifies:

> *For pre-harvest use, residual chlorine levels in the water in direct crop contact or as water from cleaning irrigation systems applied to soil must not exceed the maximum residual disinfectant limit under the Safe Drinking Water Act, except that chlorine products may be used in edible sprout production according to EPA label directions.*

The current annotation was the result of an amendment during the 2012 sunset review (77 FR 33290, June 6, 2012).

The following chlorine materials are used in organic crop production as algicides, disinfectants and sanitizers per the substance's annotation at 7 CFR 205.601(a)(2):

i. calcium hypochlorite
ii. chlorine dioxide
iii. hypochlorous acid generated from electrolyzed water
iv. potassium hypochlorite
v. sodium hypochlorite

Calcium hypochlorite, sodium hypochlorite, and chlorine dioxide were included on the National List for organic crop production with the first publication of the National Organic Program (NOP) final rule (65 FR 80548, December 21, 2000). Hypochlorous acid was added to the National List for organic crop production in 2019 (83 FR 66559, December 28, 2018). Potassium hypochlorite was added to the National List for organic crop production in 2022 (87 FR 16371, March 23, 2022). The NOSB has recommended the renewal of chlorine materials for organic crop production in 2006, 2011, 2015, and 2021 (NOSB, 2006b, 2011, 2015b, 2021a).

A manufacturer of an EPA-registered algicide product petitioned the USDA to add potassium hypochlorite to the National List for crop production in 2019 (EnviroTech Chemical Services, 2019). The NOSB recommended adding potassium hypochlorite to the National List in that same year (NOSB, 2019). In 2024, the NOSB requested a limited scope technical report on potassium hypochlorite which the NOP published in 2025 (NOP, 2025b).

FDA

The FDA maintains regulations that relate to agricultural water. For example, the FDA requires that agricultural water used for the following purposes must meet the microbial counts established at 21 CFR 112.44(a):

1. as sprout irrigation water
2. during or after harvest activities in a manner that directly contacts covered produce
3. to contact food contact surfaces or to make ice that will contact food contact surfaces
4. for washing hands during and after harvest activities

Water used for these purposes must have no detectable *Escherichia coli* (*E. coli*) in 100 ml and cannot be from untreated surface water. The FDA lists additional requirements that apply to treating agricultural water at 21 CFR 112.46.

EPA

The EPA approves the registration of sodium hypochlorite and calcium hypochlorite pesticides for use on crops, soil, and livestock to control bacteria, fungi, and slime-forming algae that can cause diseases in people and animals (EPA, 1991). The EPA also exempts calcium hypochlorite (40 CFR 180.1054), potassium hypochlorite (40 CFR 180.1300), and sodium hypochlorite (40 CFR 180.1235) from the requirement of a tolerance in food. Chlorate generated by the application of gaseous chlorine dioxide as a fungicide, bactericide, and antimicrobial pesticide is also exempted by EPA from the tolerance requirement in food (40 CFR 180.1364).

Wastewater is regulated by the EPA under the Clean Water Act (Public Law 92-500, October 18, 1972, codified at 33 U.S.C. 1251 *et seq.*). While the EPA issues guidelines for the use of reclaimed wastewater, irrigation water quality is regulated at the state, local, or tribal levels (EPA, 2012). Some jurisdictions limit the discharge of chlorinated wastewater to protect water quality and aquatic species (EPA, 1999). In certain locations, the wastewater needs to be dechlorinated before it can be released into the environment (EPA, 2012). Dechlorination is the process of removing free and combined chlorine residues by various methods. The most common dechlorination agents are sulfur dioxide, sodium bisulfite, and sodium metabisulfite, with activated carbon also used in some systems (EPA, 1999).

Post-harvest handling

Organic regulations

Synthetic substances used in post-harvest handling of organic products are listed in 7 CFR 205.601 and § 205.605, and must be used according to their annotations. Policies on post-harvest handling in USDA organic production are also described in NOP Guidance 5023: *Substances Used in Post-Harvest Handling of Organic Products* (NOP, 2024a).

FDA

Because post-harvest water quality typically poses a higher risk to food safety than other water uses related to crop and livestock production, FDA has set a zero *Escherichia coli* (*E. coli*) threshold (ALBA & NCAT, 2016). Specifically, produce that is covered under FSMA cannot use untreated surface water for washing and cooling during harvest, during packing, and holding [21 CFR 112.44(a)(2)]. Cooling and wash water must have no detectable *E. coli* in 100 ml of agricultural water [21 CFR 112.44(a)(2)]. Water used on food contact surfaces and used to make ice that contacts food is also subject to the same requirement [§ 112.44(a)(3)], as does water used for washing hands during and after harvest activities [§ 112.44(a)(4)].

Livestock

Organic regulations

The annotation for chlorine materials used for organic livestock production specifies that they are allowed for [7 CFR 205.603(a)(10)]:

> *...disinfecting and sanitizing facilities and equipment. Residual chlorine levels in the water shall not exceed the maximum residual disinfectant limit under the Safe Drinking Water Act.*

The following chlorine materials are used in organic livestock production as disinfectants, sanitizers, and medical treatments [7 CFR 205.603(a)(10)]:

i. calcium hypochlorite
ii. chlorine dioxide
iii. hypochlorous acid generated from electrolyzed water
iv. sodium hypochlorite

Calcium hypochlorite, sodium hypochlorite, and chlorine dioxide were included on the National List for organic livestock production with the first publication of the NOP final rule (65 FR 80548, December 21, 2000). Hypochlorous acid was added to the National List for organic livestock production in 2019 (83 FR 66559, December 28, 2018). The NOSB has recommended the renewal of chlorine materials for organic livestock production in 2006, 2010, 2015, and 2021 (NOSB, 2006a, 2010b, 2015d, 2021c).

In 2012, acidified sodium chlorite was petitioned to be added to the National List for use both as a disinfectant, sanitizer, and medical treatment at § 205.603(a) and as a topical treatment, for the intended use as a pre- and post-milking teat dip (Ecolab, 2012). A technical report was written in 2013 (NOP, 2013b). The NOSB recommended adding acidified sodium chlorite to the National List for both petitioned purposes at the Spring 2015 meeting (NOSB, 2015a). Acidified sodium chlorite was added to § 205.603 of the National List for organic livestock production effective January 28, 2019 (83 FR 66559, December 27, 2018). Acidified sodium chlorite appears with the following annotations [7 CFR 205.603(a)(28) and (b)(9)]:

> *Sodium chlorite, acidified—allowed for use on organic livestock as a teat dip treatment only.*

Unlike other annotations for chlorine products from other sources, § 205.603 does not limit the amount of free chlorine that can be applied from acidified sodium chlorite to organic livestock as a teat dip. The annotation here also does not specify the activating agent (citric acid) like the annotation in § 205.605(b)(1) does. The original petitioner for acidified sodium chlorite requested an annotation requiring lactic acid as the activating agent (Ecolab, 2012). Citric acid is also used as an activating agent (U.S. NLM, 2025a).

A registrant petitioned the NOSB in 2016 to consider adding hypochlorous acid to the National List as a topical treatment for livestock (Innovacyn, 2016). More specifically, the petitioner requested it be added as a wound and pinkeye treatment. The NOSB did not recommend the annotation change (NOSB, 2017).

Chlorhexidine (CAS #55-56-1) is another chlorine compound that appears on the National List as a disinfectant, sanitizer, and medical treatment [7 CFR 205.603(a)(9)]. The annotation limits its use "for medical procedures conducted under the supervision of a licensed veterinarian. Allowed for use as a teat dip when alternative germicidal agents and/or physical barriers have lost their effectiveness" [7 CFR 205.603(a)(9)]. This technical report does not include chlorhexidine because it was not specified in the work request and most of its uses and applications are different from those of other chlorine products.

Handling and processing

Organic regulations

Chlorine materials are listed as synthetic substances allowed for organic handling and processing at 7 CFR 205.605(b)(12). The annotation for chlorine materials specifies that they are for:

> *disinfecting and sanitizing food contact surfaces, equipment and facilities may be used up to maximum labeled rates. Chlorine materials in water used in direct crop or food contact are permitted at levels approved by the FDA or EPA for such purpose, provided the use is followed by a rinse with potable water at or below the maximum residual disinfectant limit for the chlorine material under the Safe Drinking Water Act. Chlorine in water used as an ingredient in organic food handling must not exceed the maximum residual disinfectant limit (MRDL) for the chlorine material under the Safe Drinking Water Act [7 CFR 205.605(b)(2)].*

The current annotation was the result of an amendment in 2018 and the amendment was implemented in 2019 (83 FR 66559, December 28, 2018).The annotation prior to this rulemaking was:

> *disinfecting and sanitizing food contact surfaces, Except, That, residual chlorine levels in the water shall not exceed the maximum residual disinfectant limit under the Safe Drinking Water Act (Calcium hypochlorite; Chlorine dioxide; and Sodium hypochlorite).*

The following chlorine materials are used in processed products labeled as "organic" or "made with organic (specified ingredients or food group(s))" [7 CFR 205.601(b)(12)]:

i. calcium hypochlorite
ii. chlorine dioxide
iii. hypochlorous acid generated from electrolyzed water
iv. sodium hypochlorite

Calcium hypochlorite, sodium hypochlorite, and chlorine dioxide were included on the National List for use in organic handling with the first publication of the NOP final rule (65 FR 80548, December 21, 2000). The USDA received a petition for hypochlorous acid generated from electrolyzed saline solution in 2015 (Botanical Food Company, 2015). The NOP published a technical report for hypochlorous acid the same year (NOP, 2015). Hypochlorous acid was added to the National List for use in organic handling in 2019 (83 FR 66559, December 28, 2018). The NOSB has recommended the renewal of chlorine materials for use in organic handling in 2006, 2010, 2015, and 2021 (NOSB, 2006c, 2010a, 2015c, 2021b).

Acidified sodium chlorite also appears on the National List [7 CFR 205.605(b)(1)]. The NOSB received a petition to add acidified sodium chlorite to the National List in 2006 (Ecolab, 2006). The NOP published a technical report for acidified sodium chlorite in 2008 (NOP, 2008). The NOSB recommended adding acidified sodium chlorite to the National List at the Spring 2009 meeting (NOSB, 2009). Acidified sodium chlorite was added to the National List for use in organic handling in 2012 (77 FR 8089, February 14, 2012). The annotation for acidified sodium chlorite allows it as a [7 CFR 205.605(b)(1)]:

> *Secondary direct antimicrobial food treatment and indirect food contact surface sanitizing. Acidified with citric acid only.*

In 2015, a manufacturer and distributor petitioned to add chlorine dioxide generated from acidified sodium chlorite to the National List for use in organic handling (ICA TriNova, 2015). The NOP published a technical report on sodium chlorite for the generation of chlorine dioxide in 2018 (NOP, 2018). Noting the availability of alternatives and the lack of public comments in support of the material, the NOSB recommended that sodium chlorite used for the generation of chlorine dioxide gas not be added to the National List at § 205.605(b) (NOSB, 2018).

FDA

Sodium hypochlorite sanitizing solutions approved as secondary direct food additives contain trisodium phosphate, sodium lauryl sulfate, and potassium permanganate [21 CFR 178.1010(b)(37)]. Magnesium oxide, and potassium bromide may also be added as optional ingredients [§ 178.1010(b)(37)]. Aqueous solutions of chlorine dioxide approved for use as a secondary direct food additive are generated from an aqueous solution of sodium chlorite with sodium gluconate, citric acid, phosphoric acid, and sodium mono- and di-dodecylphenoxybenzene-disulfonate [§ 178.1010(b)(46)].

The FDA allows sodium hypochlorite to be used directly on food to wash and lye peel fruits and vegetables [21 CFR 173.315). Products that are washed with water treated with sodium hypochlorite are required to be rinsed with potable water to remove residual chlorine to the extent possible [§ 173.315(c)]. Sodium or calcium chlorite may be used as a final sanitizing rinse on food processing equipment (§ 178.1010). The FDA also permits direct food use of chlorine dioxide to wash fruits and vegetables, and in poultry processing (§ 173.300). The maximum amount of chlorine dioxide allowed is 3 ppm for poultry processing [§ 173.300(b)(1)] and 3 ppm for fruits and vegetables, followed by a potable water rinse, blanching, cooking, or canning [§ 173.300(b)(2)].

USDA FSIS

The FSIS requires poultry contaminated with digestive tract contents and reprocessed off-line to be treated with chlorinated water with 20-50 ppm of available chlorine or another approved antimicrobial substance [9 CFR 381.91(b)(2)]. FSIS also mandates the use of sodium hypochlorite to disinfect facilities and equipment that has been contaminated by polluted water (§ 381.151).

EPA

The Organic Foods Production Act (OFPA) [7 U.S.C. 6510(a)(7)] requires water used as an ingredient in an organic processed product to meet SDWA (42 U.S.C. subchapter XII) requirements. The EPA established MRDLs of 4.0 mg/L for chlorine (as Cl_2), 4.0 mg/L for chloramines (as Cl_2), and 0.8 mg/L for chlorine dioxide (as ClO_2) [40 CFR 141.65(a)]. In addition, the EPA established Maximum Contaminant Levels (MCLs) for the chlorine disinfection by-products total trihalomethanes of 0.080 mg/L and haloacetic acids of 0.060 mg/L [40 CFR 141.64(b)(1)]. The response to _Evaluation Question #3_ explains the formation of these and other disinfection by-products.

Action of the Substance

Elemental chlorine (Cl) is a highly-reactive halogen that readily receives electrons (Schmittinger et al., 2011). Molecular chlorine (Cl_2) is a strong oxidizing and chlorinating agent (Bommaraju et al., 2002). Hypochlorous acid (HOCl) is the most effective form of chlorine for killing microbial pathogens and parasites that pose food safety risks (Bihn & Reiners, 2018; Suslow, 1997).

Chlorine substances are composed of different distinct chemical species with different properties and chemical activities. Chlorine's disinfection properties relate to its ability to oxidize, or take electrons away from other chemical compounds (Occidental Chemical Corporation, N.d.). Chlorine can exist in a range of oxidation states, from (-1) to (+7) (Schmittinger et al., 2011).[1] To form the (-1) oxidation state, a chlorine atom *gains* a single additional electron, completing its outer valence of 8 electrons and becoming a negatively charged chlorine ion, Cl^- (Schmittinger et al., 2011). When chlorine *loses* an electron, it develops a (+1) oxidation state. Chlorine develops a (+1) oxidation state in substances like hypochlorous acid and hypochlorite, (+5) oxidation state in chlorates, and (+7) oxidation state in perchlorates (Schmittinger et al., 2011). When chlorine is saturated with electrons [(-1) oxidation state], it cannot oxidize other substances; however, when in a neutral oxidation state (as with chlorine gas, Cl_2) or positive oxidation state (such as in the case of hypochlorous acid), it reacts with other compounds by oxidizing them (removing their electrons) (Occidental Chemical Corporation, N.d.).

Chloride

Chloride salts are commonly found in nature, with sodium chloride (NaCl, or common table salt) as the most abundant source for the production of chlorine materials (American Chemistry Council, 2025; Schmittinger et al., 2011). Sodium chloride is an essential electrolyte that is required by all life (Feldman, 2005). The chloride anion (Cl^-) that results from dissolving salts is relatively stable, very mobile, and much less reactive than other forms of chlorine (Gowariker, 2009).

Reactive chlorine species are broad spectrum antimicrobials that kill a wide range of microorganisms (Gray et al., 2013). These have different oxidation states that cause them to behave differently, as described in greater detail below. For this technical report, the most significant and relevant species of chlorine are:

- the hypochlorite ion (ClO^-) that is a moiety with hypochlorous acid and the various hypochlorite salts and an oxidation state of +1
- chlorine dioxide (ClO_2) with an oxidation state of +2 and the chlorite ion (ClO_2^-) with an oxidation state of +3
- the chlorate (ClO_3^-) and perchlorate ions (ClO_4^-) with oxidation states of +5 and +7 respectively

[1] Note that the oxidation state is not an indicator of how strongly a substance will react with another material. This will depend on various factors, including the solution composition, its pH, and how these affect their reduction potentials. Oxidation numbers only describe how many electrons a substance can accept or donate before it is neutrally charged.

Hypochlorite

Hypochlorites are often considered the most active chlorine sanitizers used in food handling (Fatica & Schneider, 2009). These have chlorine in an oxidation state of (+1) (Schmittinger et al., 2011). The biocidal mode of action is discussed in greater detail in *Evaluation Question #4*.

When chlorine is added to water, it goes into solution as hypochlorous acid, a hydrogen ion, and a chloride ion (see *Equation 1*) (Bommaraju et al., 2002; National Research Council & Safe Drinking Water Committee, 1980). As we noted in the description of chloride salts (see *Action of the Substance*), the chloride anion has little to no ability to oxidize other substances; only the hypochlorous acid contains chlorine capable of oxidizing (bleaching) other substances.

$$Cl_2 + H_2O \rightleftharpoons HOCl + H^+ + Cl^- \qquad \text{Equation 1}$$

(Chlorine) + (Water) ⇌ (Hypochlorous acid) + (Hydrogen ion) + (Chloride ion)

Chlorine's solubility decreases with increasing temperatures (Bommaraju et al., 2002).

Hypochlorous acid decomposes into a hydrogen ion and a hypochlorite ion (see *Equation 2*) (National Research Council & Safe Drinking Water Committee, 1980). This reaction is dependent on pH; as the pH of an aqueous solution decreases, hypochlorous acid will predominate. The pKa for hypochlorous acid is around 7.5 (Andrés et al., 2022). Therefore, at pH 7.5, equal amounts of hypochlorous acid and hypochlorite will exist. At a pH above 7.5, the hypochlorite ion will begin to predominate. Since hypochlorous acid is more biologically active than hypochlorite (Marriott et al., 2018), this relationship with pH is very important.

$$HOCl \rightleftharpoons H^+ + ClO^- \qquad \text{Equation 2}$$

(Hypochlorous acid) ⇌ (Hydrogen ion) + (Ionic hypochlorite)

The effective amount of chlorine for oxidative reaction and disinfection may be referred to as *free chlorine, reactive chlorine,* or *available chlorine* (Suslow, 1997). It does not include the chloride anions in solution.

Chlorates

Chlorate refers to the ClO_3^- anion. With an oxidation state of (+5), chlorate compounds are strong oxidizers that can react violently with virtually any combustible material (Sandin et al., 2015). They can be used to form more stable perchlorate (ClO_4^-) ions that are more commonly used in industrial applications (Sandin et al., 2015). Hypochlorous acid and ionic hypochlorite decompose into chlorate, hydrogen, and chloride anions (see *Equation 3*) (Sandin et al., 2015).

$$2HOCl + OCl^- \rightarrow ClO_3^- + 2H^+ 2Cl^- \qquad \text{Equation 3}$$

(Hypochlorous acid) + (Ionic hypochlorite) → (Chlorate) + (Hydrogen ions) + (Chlorine ions)

Perchlorate

The perchlorate ion (ClO_4^-) and various perchlorate compounds can also be formed as disinfection by-products from chlorine treatment of water (Rao et al., 2012). These compounds contain chlorine in the (+7) oxidation state. The kinetics are complicated and involve photodecomposition under specific conditions involving exposure to sunlight or UV light (Rao et al., 2012).

Chlorite

Chlorite is the anionic form of chlorine dioxide (ClO_2^-) (U.S. NLM, 2025b). It is a highly unstable gas and can be explosive if mishandled. These compounds contain chlorine with an oxidation state of (+3). Sodium chlorite ($NaClO_2$) goes into solution as sodium and chlorite ions (see *Equation 4*) (JECFA, 2008).

$$NaClO_2 \rightarrow ClO_2^- + Na^+ \qquad \text{Equation 4}$$

(Sodium chlorite) → (Chlorite anion) + (Sodium cation)

Addition of an acid generates chlorous acid, which is the active disinfectant (see *Equation 5*) (JECFA, 2008).

$$ClO_2^- + H^+ \rightarrow HClO_2 \qquad \text{Equation 5}$$

(Chlorite anion) + (Hydrogen cation) → (Chlorous acid)

Evaluation Questions

The crops, livestock, and handling subcommittees all requested information on Evaluation Question #7, which are similar questions in the crops/livestock technical report template, and the handling/processing technical report template. The crops and livestock committees also requested information on Evaluation Questions #3, #4, #6, and #9 from the crops/livestock technical report template. Additional information is also included regarding post-harvest handling. The Focus Questions address all three scopes.

References to chlorine materials below are made with respect to generic formulations or solutions unless brand names are specified. Experiments are often performed with a small concentration of active chlorine with the balance assumed to be water. In most cases, the literature we reviewed for this technical report did not include information on the specific formulations used or whether they contained stabilizers or synergists that enhanced chlorine efficacy. Some of the trademarked or brand names are also used as generic descriptors in various publications cited (Chalker-Scott, 2013; Irakoze et al., 2022; Marriott et al., 2018).

Classification of the Substance

Evaluation Question #3: Describe any known chemical interactions between this substance and other substances used in organic crop or livestock production or handling [7 U.S.C. 6518(m)(1)].
Chlorine materials interact with substances used in organic crop and livestock production, and in post-harvest handling. Free chlorine is highly reactive with organic matter and many other categories of substances that include those allowed for use in organic production and handling (EPA, 1994; Schmittinger et al., 2011). Advances in the study of chlorine and other chemistry resulted in the development of many pesticides and other modern agrochemicals (Jeschke, 2010).

Disinfection by-products
Most studies of the effects of chlorine on organic matter focus on the disinfection by-products in drinking water and waste water treatment (Mazhar et al., 2020; Simpson & Mitch, 2022; Westerhoff et al., 2004). Disinfection by-products are the resulting chemicals formed when chlorine materials react with organic matter. The first discovered disinfection by-products were trihalomethanes (Cotruvo, 1981; de Castro Medeiros et al., 2019; Rook, 1977). Trihalomethanes are a family of compounds derived from methane that have three of the four hydrogen atoms replaced by halogens, such as chlorine, fluorine, bromine, or iodine (40 CFR 141.2). Chloroform ($CHCl_3$, also known as trichloromethane) was the first trihalomethane discovered in chlorinated water and many others were identified soon thereafter (Rook, 1977). The intermediates created by the chlorination of humic acids that lead to the eventual formation of chloroform and other trihalomethanes have been studied extensively (Alexandrou et al., 2018; Asadollahi et al., 2025; Bond et al., 2012; De Leer et al., 1985; Koltsova, 2019). Over 600 disinfection by-products are potentially formed by wastewater treatment (Alexandrou et al., 2018).

Other important disinfection by-products include (Alexandrou et al., 2018; Barrett et al., 2000; Bond et al., 2012; Forster et al., 2025):
- haloacetic acids (HAAs)
- nitrosamines (NAs)
- haloacetonitriles (HANs)
- haloacetamides (HAMs)
- haloacetaldehydes (HALs)
- haloketones (HKs)
- halonitromethanes (HNMs)

Trihalomethanes and haloacetic acids account for about 80% of all disinfection by-products (Koltsova, 2019). Disinfection by-product toxicity is discussed further in *Evaluation Question #4*.

Chloroform and other trihalomethanes have been observed to occur naturally in some soils (Hoekstra et al., 1998; Huber et al., 2009). The formation of natural trihalomethanes from soil organic matter is not fully understood, and may have both abiotic and biotic pathways (Breider & Albers, 2015). Microorganisms are also capable of producing reactive chlorine species, hypothetically as a defense mechanism to suppress competing organisms (Bengtson et al., 2009). The small amount of reactive chlorine species produced by these microorganisms reacting with organic matter may play a significant role in trihalomethane formation (Bengtson et al., 2009).

Focus Question #2 further explores the conditions under which trihalomethanes and other disinfection by-products are generated.

Absorption into food

Some foods that are chlorinated or treated with chlorinated water during processing and handling will take up chlorine, including flour, meat, and poultry products (Fukayama et al., 1986). Milk will also absorb residual chlorine and its disinfection by-products both on the farm and during dairy processing (Paludetti et al., 2019; Twomey et al., 2024).

Soft wheat flour chlorinated at room temperature at five different levels ranged from 4.8 to 24.0 mg/kg; all had elevated chloride levels compared to unbleached flour (Sollars, 1961). Chlorine absorption was almost 100% at the lower doses and diminished at the higher doses (Sollars, 1961). Most of the added chloride was recovered from the gluten and water-soluble fractions of the flour and not from the starch (Sollars, 1961). In addition to chloride, researchers later determined that chlorinated flour can contain detectable levels of chloroform and other chlorination by-products (Fukayama et al., 1986). The fractions of flour that were most likely to take up chlorine and generate chloroform were the lipids and water-insoluble portion of the defatted flour (C. Wei et al., 1984).

Animal products will absorb available chlorine in lipid tissue that will then react with fatty acids to form chloroform (Fukayama et al., 1986). While most of the available chlorine in poultry chiller water will go into solution as chloride and be removed from the effluent, at higher doses some will be retained by the carcasses as chloroform or other disinfection by-products (Fukayama et al., 1986).

In one experiment, chicken frankfurters were immersed in water chlorinated at 40, 100, 200, and 400 ppm of hypochlorite and the chlorine uptake was measured at 1 hour, 4 hours, and 24 hours (Tsai et al., 1993). Chlorine uptake by the frankfurters was positively correlated with hypochlorite concentrations. Most of the chlorine was taken up in the first hour, with chlorine diminishing over time (Tsai et al., 1993).

A study in Ireland tracked the chlorate, perchlorate, and trichloromethane levels from residual sanitizers used on 67 dairy farm bulk milk tanks (Paludetti et al., 2019). The study also tracked iodine residues from teat disinfectants. Samples were taken from bulk tanks, collection tanks, the whole milk silo, the skim milk silo, the cream silo, and skim milk powder. Trichloromethane was detected in all farm bulk tank samples, and chlorate and perchlorate were detected in 14 out of 67 farm bulk tank samples. The trichloromethane concentrated in the cream was removed in the skimming process and none was detected in the skim milk powder (Paludetti et al., 2019).

The toxicological implications of these findings are discussed further in Focus Question #2.

Interactions with irrigation water and equipment

The increased use of chlorinated wastewater for irrigation has created interest in the evaluation of the environmental impact of chlorine on soil health (A. Singh, 2021; Song et al., 2017, 2019). Water from waste effluent has been reclaimed for irrigation for centuries and has been valuable for food production, but also can be a source of pathogens when not properly treated (A. Singh, 2021). As a result, wastewater is often treated before it is released for the irrigation of food crops to reduce risk of foodborne pathogen (Benami et al., 2016; A. Singh, 2021). Chlorine disinfectants are commonly used to treat wastewater (Phlaengsattra et al., 2024; A. Singh, 2021). Irrigation water from such sources is expected to have elevated levels of chlorine and chlorinated disinfection by-products (Murrell et al., 2021; Phlaengsattra et al., 2024). Agricultural wastewater can also have elevated levels of chlorine and disinfection by-products (Czarnecki et al., 2024).

Chlorine in irrigation lines will react with iron in solution to oxidize the ferrous form of iron (Fe^{2+}) into the ferric form (Fe^{3+}), precipitating as ferric hydroxide which can clog irrigation lines (Maynard & Hochmuth, 1997).

Interactions with cows, dairy equipment, and milk

Chlorine and its disinfection by-products can contaminate milk in equipment and bulk milk tanks that have been sanitized with chlorinated water (Fischer et al., 2011; McCarthy et al., 2018; Ryan et al., 2012). Halogenated teat dips, such as acidified sodium chlorite and iodophors, are another potential source of trihalomethanes and other disinfection by-products contaminants in the milk supply chain (Fischer et al., 2011; Slattery & Garvey, 2025). Disinfection by-products found in the milk supply include trihalomethanes (McCarthy et al., 2018; Ryan et al., 2012), chlorites (Fischer et al., 2011), chlorates, and perchlorates (Fischer et al., 2011; McCarthy et al., 2018). Free chlorine residues cause taste and odor sensory defects in milk (Kemmerling et al., 2025). Residual chlorine will inhibit organisms responsible for making fermented and cultured dairy products, such as cheese (Cremonesi et al., 2020). Most importantly, chlorine disinfection by-products pose a public health risk by exposing people to probable carcinogens and other oncogenic substances (Slattery & Garvey, 2025). Some disinfection by-products in milk and dairy products are endocrine disruptors (Nobile et al., 2022). Chlorine products' toxicity are explored further in Evaluation Question #4 and human health effects are discussed in greater detail in Evaluation Question #6.

Chlorate enters the food supply almost exclusively as a disinfection by-product through the use of chlorine-based sanitizers in food production (McCarthy et al., 2018). Disinfection by-products found in the milk supply have been linked to the use of hypochlorous acid, hypochlorites, and chlorine dioxide (McCarthy et al., 2018). The use of chlorine-based sanitizers throughout the cleaning process in CIP systems, that is not followed by a sufficient clean water or acid rinse, is one of the leading causes of milk contaminated with disinfection by-products (McCarthy et al., 2018). Because of quality and food safety concerns, the Republic of Ireland prohibited the use of chlorine disinfectants in CIP systems starting in 2021 (Twomey et al., 2023, 2024).

Other chemical interactions

Researchers have reported that increasing the acidity of a solution also increases the efficiency of chlorine as a sanitizer. Reducing the pH of sanitizing solutions increases the sensitivity of *Salmonella typhimurium* to chlorine treatment (Leyer & Johnson, 1997).

Evaluation Question #4: Discuss (A) the toxicity and mode of action of this substance; (B) the toxicity and mode of action of its breakdown products or any contaminants; and (C) their persistence and areas of concentration in the environment [7 U.S.C. 6518(m)(2)].

(A) Describe whether this substance has been reported to have toxic effects and if its mode of action can cause adverse health and/or environmental effects.

Given that chlorine materials have a wide range of uses and applications as antimicrobial pesticides, and they are listed under all three scopes of the USDA organic regulations, the answers to these Evaluation Questions apply generally to crops, livestock, and handling unless specifically noted otherwise.

Chlorine toxicity in microorganisms

"Available chlorine's" antimicrobial activity is still not fully understood, and researchers have formed various hypotheses explaining its broad-spectrum toxicity and rapid action (Marriott et al., 2018). Among the proposed hypotheses are that available chlorine acts as a disinfectant and sanitizer in the following ways (Marriott et al., 2018):

- oxidizes specific enzymes important for carbohydrate metabolism
- destroys various key enzymes resulting in metabolic imbalances
- disrupts protein synthesis
- oxidizes and decarboxylizes amino acids
- reacts with nucleic acids, nucleotides, and other essential biomolecules to denature them or form toxic substances[2]
- inhibits oxygen uptake and phosphate synthesis
- causes macromolecules to leak from damaged cells
- induces deoxyribonucleic acid (DNA) lesions that cause the loss of DNA-transforming ability[3]
- creates chromosomal aberrations

Chlorine toxicity in animals

Table 3 summarizes the environmental toxicity of reactive chlorine and its sources, identifying the product, affected species, exposure level, toxicity, and source. Sodium and calcium hypochlorite are highly toxic to freshwater fish and invertebrates (EPA, 1991). The aquatic invertebrate *Daphnia magna* is particularly sensitive (EPA, 1986). One study showed 100% mortality in 5.5 hours with chlorine concentrations in effluent water of 0.220 mg/L, and another showed 100% mortality in effluent water with available chlorine concentrations of 0.070 mg/L with an exposure time of 10.5 hours (Ward & DeGraeve, 1978). Saltwater and anadromous fish (those that travel from the sea upriver to spawn) are more resistant to chlorine toxicity. Elevated temperatures in sea water increased chlorine's toxicity to coho salmon (*Oncorhynchus kisutch*) and shiner perch (*Cymatogaster aggregata*) (Stober et al., 1980).

Sodium chlorite (not to be confused with sodium *chloride*) in solid form is a strong oxidizer that is highly unstable and can ignite fires and cause explosions if mishandled (Langerman, 2021). It is relatively stable in aqueous form (Langerman, 2021). The chlorite ion produces methemoglobin (a form of hemoglobin unable to carry oxygen) when ingested by rats and cats, and humans (Gosselin et al., 1984). Rainbow trout (*Oncorhynchus mykiss*) are sensitive to exposure to sodium chlorite and the dissociated free chlorite ion release by chlorination, but the toxicity is lower than that of free chlorine (Svecevičius et al., 2005).

[2] For example, chlorine forms toxic N-chloro derivatives of the nucleotide cytosine (Marriott et al., 2018).
[3] DNA transformation ability is the capacity of a cell to take up and incorporate exogenous DNA. The mechanism is considered a key means of bacterial mutation and selection for resistance to antimicrobials (C. Zhang et al., 2023).

The EPA considers sodium and calcium hypochlorite to be low risk to both upland game birds (quail) and waterfowl (ducks) (EPA, 1992). However, members of the parrot family (*Psittacine*) may be susceptible to sodium hypochlorite when it is used to clean their facilities (Wilson et al., 2001).

Table 3: Environmental toxicity of available chlorine and selected chlorine products

Chlorine product/model species-exposure	Exposure & toxicity	Source
Free chlorine		
Water flea (*Daphnia magna*)	96 hr LC_{50}: 0.017 mg/L	(Ward & DeGraeve, 1978)
Fathead minnow (*Pimephales promelas*)	96 hr LC_{50}: 0.082- 0.095 mg/L	(Ward & DeGraeve, 1978)
Rainbow trout (*Oncorhynchus mykiss*)	96 hr LC_{50}: 0.069 mg/L	(Ward & DeGraeve, 1978)
Largemouth bass (*Micropterus salmoides)*	96 hr LC_{50}: 0.241 mg/L	(Ward & DeGraeve, 1978)
Hypochlorite salts		
Water flea (*Daphnia magna*)	48 hr LC_{50} (hypochlorite salts): 0.037 – 2.3 ppm	(EPA, 1992)
Upland game bird (Bobwhite quail)	Oral LD_{50} (Na) >2,510 mg/kg	(EPA, 1992)
Upland game bird (Bobwhite quail)	Oral LD_{50} (Ca) 3,474 mg/kg	(EPA, 1992)
Waterfowl (duck)	LC_{50} (hypochlorite salts): >5,000 mg/kg	(EPA, 1992)
Chlorine dioxide		
Rainbow trout (*Oncorhynchus mykiss*)	Adult 96 hr LC_{50}: 8.3 mg/L	(Svecevičius et al., 2005)

Table 4 provides the results of toxicological experiments on model laboratory animals. The hypochlorous acid salts are less toxic than chlorine dioxide or sodium chlorite (Lewis, 2004).

Table 4: Acute mammalian toxicity of chlorine materials

Chlorine product/model species-exposure	Exposure & toxicity[4]	Source
Calcium hypochlorite		
Rat	Oral LD_{50}: 850 mg/kg	(Fisher, 2021; Lewis, 2004)
Rabbit	Dermal LD_{50}: >2,000 mg/kg	(Fisher, 2021)
Chlorine dioxide		
Rat	Oral LD_{50}: 292 mg/kg	(Lewis, 2004)
Rat	Inhalation LC_{50}: 500 mg/kg	(Lewis, 2004)
Sodium chlorite		
Rat	Oral LD_{50}: 165 mg/kg	(Lewis, 2004)
Mouse	Oral LD_{50}: 350 mg/kg	(Lewis, 2004)
Guinea pig	Oral LD_{50}: 300 mg/kg	(Lewis, 2004)
Sodium hypochlorite		
Mouse	Oral LD_{50}: 5,800 mg/kg	(Lewis, 2004)
Rat	Oral LD_{50}: 8,200 mg/kg	(Clorox, 2019b)
Rabbit	Oral LD_{50}: >10,000 mg/kg	(Clorox, 2019b)

The toxicity data in the potassium hypochlorite technical review was based on sodium hypochlorite (NOP, 2025b). The EPA based potassium hypochlorite's pesticide registration on data extrapolated from sodium hypochlorite (76 FR 11340, March 02, 2011). Hypochlorites are broad-spectrum antimicrobial pesticides that are highly toxic to gram-positive and gram-negative bacteria (Gallandat et al., 2021).

Removal of chlorine from treated effluent can reduce toxicity to non-target species (Brungs, 1973; Zillich, 1972).

Chlorine toxicity in humans

Chlorine's toxicity in humans depends on the concentration of available chlorine, exposure route, and duration of exposure (Winder, 2001). Toxicity is also a function of the product that generates the available chlorine (Lewis, 2004). Other health impacts are covered in greater depth in *Evaluation Question #6*.

Chlorine gas

Chlorine gas is toxic to humans when inhaled (Achanta & Jordt, 2021; Klaassen, 2001; NIOSH, 2011; C. W. White & Martin, 2010; Winder, 2001). Because of its toxicity, chlorine gas has been used in chemical warfare (Achanta & Jordt, 2021; Klaassen, 2001; Squadrito et al., 2010; Winder, 2001). Employers need to limit concentrations in the workplace to prevent occupational injuries (Achanta & Jordt, 2021; Cheremisinoff, 1999; NIOSH, 2011; Winder, 2001).

The majority of deaths caused by chlorine exposure occur within 24 hours due to respiratory failure (NIOSH, 2011). Chlorine is severely irritating to the eyes, nose, throat, upper respiratory tract, and skin (NIOSH, 2011). At high exposure levels, chlorine will immediately cause fluid to accumulate in the lungs (pulmonary edema) that will develop into severe pulmonary congestion that can be fatal (Winder, 2001). Depending on the concentration and

[4] LC_{50} = Median Lethal Concentration; LD_{50} = Median Lethal Dose (INCHEM, 1998).

duration of the exposure, inhalation can result in (Achanta & Jordt, 2021; Winder, 2001) lacrimation (discharge of tears), rhinorrhea (runny nose), bronchospasms (narrowing of airways), coughing, dyspnea (shortness of breath), acute lung injury, and death.

Hypochlorous acid and its salts
There is no evidence that hypochlorite salts or chlorinated drinking water are carcinogenic (IARC, 1991).

Sodium hypochlorite is mildly toxic by ingestion (Lewis, 2004). However, it will release chlorine gas and hypochlorous acid under ordinary conditions, both of which are more toxic than the ingestion of sodium hypochlorite (Luttrell, 2001). For example, hypochlorous acid is an experimental teratogen (Lewis, 2004).[5] Mixing sodium hypochlorite with vinegar or ammonia will release large amounts of chlorine gas, posing a public health hazard (Philipp et al., 1985). Sodium hypochlorite is irritating to the eyes and can cause permanent eye injury at higher concentrations (Luttrell, 2001).

Chlorine dioxide
Chlorine dioxide is moderate toxic by inhalation (Lewis, 2004). Symptoms of chlorine dioxide inhalation include coughing, wheezing, eye and throat irritation, headache, vomiting, bronchitis, rhinitis (nasal inflammation), dyspnea (shortness of breath), and pulmonary edema (Gosselin et al., 1984). Experimental exposure to chlorine dioxide has been linked to reproductive effects and mutation (Lewis, 2004).

Incident data
Table 5 contains the number of incidents reported to the EPA's Incident Data System between September 1, 2010 and September 1, 2025 (EPA, 2025b). During that period, EPA received 556 reported incidents that involved sodium hypochlorite. Most involved humans and were classified as either minor or moderate. However, four incidents resulted in human fatalities. Only three sodium hypochlorite incidents involved animals, and none were fatal. During that same period, there were 88 incidents reported for calcium hypochlorite, four for sodium chlorite, two for chlorine dioxide, one for hypochlorous acid, and none for potassium hypochlorite. None of these resulted in human fatalities, although one animal fatality was linked to calcium hypochlorite during that period (EPA, 2025b).

Table 5: Chlorine antimicrobial pesticide incidents reported to EPA between 2010 and 2025 (EPA, 2025b)

Substance	Incidents	Human fatalities	Animal fatalities
Sodium hypochlorite	556	4	0
Calcium hypochlorite	88	0	1
Sodium chlorite	4	0	0
Chlorine dioxide	2	0	0
Hypochlorous acid	1	0	0
Potassium hypochlorite	0	0	0

(B) Describe whether this substance's contaminants, or any of its breakdown products have been reported to have toxic effects and are capable of causing adverse health and/or environmental effects either present in this substance or arising from the degradation of this substance over time.
Elemental chlorine (Cl) is not classified as a carcinogen (NIOSH, 2011). However, free chlorine can react with various synthetic and nonsynthetic compounds to form disinfection by-products that can cause adverse health and environmental effects (Barrett et al., 2000; Bond et al., 2012; Mazhar et al., 2020; National Research Council & Safe Drinking Water Committee, 1987). Trihalomethanes are also the most common and most researched disinfection by-products from chlorine treatment of water (Bond et al., 2012; Cotruvo, 1981; de Castro Medeiros et al., 2019; Nikolaou & Lekkas, 2001). Various chlorate (ClO_3^-) and perchlorate (ClO_4^-) compounds are also disinfection by-products (Rao et al., 2012; Sandin et al., 2015).

Disinfection by-product toxicity in humans
The greatest toxicological concern is with trihalomethanes in the drinking water supply (Cotruvo & Amato, 2019). The U.S. National Cancer Institute classified the trihalomethane known as chloroform as a carcinogen in 1976 (National Cancer Institute, 1976). The classification led the EPA to take regulatory action to set limits on trihalomethanes in public drinking water under its authority in the SDWA (42 U.S.C. 300f *et seq.*). Much of the evidence of the chronic toxicity of trihalomethanes and other disinfection by-products is based on animal models and is reported separately in the section *Disinfection by-product toxicity in animals*.

Establishing whether a given substance is carcinogenic to humans is complicated by different paradigms regarding the validity of animal models, the difficulty of conducting epidemiological research, and ethical considerations (Cogliano et al., 2004). The EPA's risk assessment of the public health risks from chlorination of drinking water

[5] A teratogen is a substance, agent, or process that can interfere with normal embryonic or fetal development, causing birth defects or developmental malformations.

relied on *"inherently difficult and incomplete empirical analysis"* (EPA, 2005b). The complex nature of disinfection by-products as a highly variable mixture of chemicals, combined with conflicting public health and regulatory objectives makes a risk assessment of their human health impacts challenging (Grellier et al., 2015).

The authors of a meta-analysis that reviewed 40 studies assessed the human health risks associated with disinfection by-products in drinking water and concluded that most articles had weaknesses that reduced the reliability and utility of their results (Grellier et al., 2015). The studies used various models and methodologies that prevented direct comparisons between studies. Several of the studies relied on estimates of disinfection by-products levels in public water supplies that were extrapolated into dose responses based on estimates of water consumption and other exposure routes. Others used the regulatory maximum to estimate general cancer rates at the upper limit of exposure, rather than empirical data on actual doses and exposures (Grellier et al., 2015).

While researchers consistently found evidence that certain disinfection by-products produced by the chlorination of water are genotoxic, the implications for exposure and human health need to be confirmed through epidemiological studies (Cortés & Marcos, 2018). According to Anand and Mehendale (2005), epidemiological evidence that trihalomethanes cause cancer in humans is equivocal and inconclusive. Other disinfection by-products may have greater genotoxicity and carcinogenicity (Richardson et al., 2007). The strongest evidence points to increased incidents of bladder cancer related to the consumption of chlorinated water (Cantor et al., 1998; EPA, 2005a; Grellier et al., 2015; Villanueva et al., 2003, 2004).

A meta-analysis of eight studies examined the association of chlorinated drinking water with bladder cancer (Villanueva et al., 2003). The authors reviewed data from six case-control studies and two cohort studies that were considered to be valid. The studies were conducted in the USA, Canada, and Finland. The case-control studies had a combined number of 6,084 bladder cancer incidents stratified by age, sex, and years of exposure to chlorinated water. One of the case-control studies also included smoking as a possible contributing factor to bladder cancer. The cohort studies identified populations that were exposed to chlorinated drinking water and unchlorinated drinking water. A combined number of 124 incidents of bladder cancer were reported in the cohort study. All eight studies reported elevated risk of bladder cancer in populations exposed to chlorinated drinking water. The authors of the review concluded that the consumption of chlorinated water poses a moderate excess risk for bladder cancer. Men exposed to chlorinated drinking water had a higher risk of bladder cancer than women. Subjects that consumed chlorinated drinking water for over 40 years had a clear excess risk (Villanueva et al., 2003).

In a study in Iowa, researchers investigated the effect of trihalomethanes on bladder cancer rates across 222 public water supplies (Cantor et al., 1998). In that study, there were 1,716 confirmed bladder cancer cases, and 1,617 matched controls. Participants were sent a mail questionnaire about their water consumption, period of residence in the water supply service area, occupational history, and smoking history. The authors obtained trihalomethane data from the water suppliers. The results showed that men who smoked and were exposed to water with elevated trihalomethanes had a significantly higher risk of bladder cancer than people who never smoked or were not exposed to trihalomethanes in drinking water (Cantor et al., 1998).

Researchers conducted a subsequent detailed analysis of bladder cancer risk pooling data from the USA, Canada, France, Italy, and Finland (Villanueva et al., 2004). The study included 2,806 confirmed bladder cancer cases and 5,254 controls, all of whom had a 40-year exposure window. The subjects completed a survey that included their age, sex, occupation, education, smoking status, and total fluid consumption, including water, coffee, and other possible sources of exposure. The researchers also obtained trihalomethane data from water suppliers. The authors concluded that after controlling for other factors such as smoking and high-risk occupations, men exposed to trihalomethanes for over 40 years faced a significantly higher risk of bladder cancer than men who were not exposed to trihalomethanes. Bladder cancer incidents in men were positively correlated with the levels of trihalomethanes in the water they consumed (Villanueva et al., 2004).

Decreased bladder cancer is assumed to be the primary health benefit for establishing MCLs trihalomethanes in drinking water (EPA, 2005a). The EPA has identified four trihalomethanes and five haloacetic acids of concern as disinfection by-products in drinking water (40 CFR 141.2). Haloacetic acids have the structure of acetic acid, but with one or more halogens (such as chlorine) replacing at least one of the hydrogen atoms.

The trihalomethanes of concern are (40 CFR 141.2):

- chloroform ($CHCl_3$)
- bromoform ($CHBr_3$)
- bromodichloromethane ($CHBrCl_2$)
- dibromochloromethane ($CHBr_2Cl$)

The haloacetic acids of concern are (40 CFR 141.2):
- monochloroacetic acid ($ClCH_2CO_2H$)
- dichloroacetic acid (Cl_2CHCO_2H)
- trichloroacetic acid (Cl_3CCO_2H)
- monobromoacetic acid ($BrCH_2CO_2H$)
- dibromoacetic acid (Br_2CHCO_2H)
- bromochloroacetic acid ($BrClCHCO_2H$)

The EPA established an MCL of 0.08 mg/L for total trihalomethanes and 0.06 mg/L for the five haloacetic acids in drinking water [40 CFR 141.64(b)(1)(i)]. The EPA also established an MCL of 1.0 mg/L for chlorite [40 CFR 141.64(a)]. Ongoing research continues to identify newly discovered disinfection by-products . For example, naturally occurring iodide in water reacts with hypochlorous acid to generate hypoiodous acid (HOI), which in turn reacts with organic matter to form iodine-containing acids (Forster et al., 2025). These iodinated disinfection by-products may be more cytotoxic and genotoxic than the regulated disinfection by-products, trihalomethanes, and haloacetic acids (Forster et al., 2025; Richardson et al., 2007).

Trihalomethanes are formed by free chlorine reacting with natural organic matter, humic acids, and fulvic acids in water (de Castro Medeiros et al., 2019; Goslan et al., 2009; Johnson et al., 1982; Rook, 1977). Increased generation of trihalomethanes is positively correlated with both greater concentrations of available chlorine and higher levels of organic matter (Bond et al., 2012). Drinking water is the primary source of human exposure to trihalomethanes and other disinfection by-products (Mazhar et al., 2020; Villanueva et al., 2007). Other sources of exposure are inhalation and skin (dermal) contact (Mazhar et al., 2020). Trihalomethanes in milk are regarded as a public health risk (McCarthy et al., 2018; Ryan et al., 2013).

Pregnant women exposed to disinfection by-products from water chlorination may experience various adverse reproductive outcomes, including low birth weight, increased birth defects, stillbirths, and miscarriages (Grellier et al., 2010; Nieuwenhuijsen et al., 2000; Sharma et al., 2009; Summerhayes et al., 2021). Researchers have conducted meta-analyses of the association of the exposure of pregnant women to disinfection by-products and adverse birth outcomes (Grellier et al., 2010; Summerhayes et al., 2021).

The authors of one meta-analysis of 15 studies evaluated whether disinfection by-product exposure increased risks to fetal growth and premature birth (Grellier et al., 2010). Most of the studies were based on trihalomethane exposure through drinking water. The authors of the meta-analysis found that there was no evidence that trihalomethanes impaired fetal development (Grellier et al., 2010).

In contrast, another meta-analysis focused on fetal development and whether exposure to disinfection by-products during pregnancy resulted in fetal development and births that were small for their gestational age (Summerhayes et al., 2021). The authors reviewed 16 studies that evaluated risks to fetal development in 19 populations. All the articles included exposure to trihalomethanes through drinking water, with studies published after 2005 also including haloacetic acids. The authors of the meta-analysis concluded that exposure to disinfection by-products increases the risk of decreased fetal size (Summerhayes et al., 2021).

A literature review of both animal and epidemiological studies explored adverse reproductive outcomes in both animal and epidemiological studies (Sharma et al., 2009). As with the meta-analysis, not all studies supported evidence of adverse outcomes (Sharma et al., 2009). Most reproductive studies that showed positive results for such outcomes were of populations exposed in the range of 80-100 µg/L (0.08-0.10 mg/L) (Sharma et al., 2009). These exposures are above SDWA's MRDL. However, epidemiological evidence shows such a correlation extends to populations exposed to total trihalomethanes within the SDWA limits. One notable exception was a study conducted in Massachusetts, where infants exposed during pregnancy to higher levels of total trihalomethanes in the drinking water supply had lower average birth weights (Wright et al., 2003).

Other chlorine disinfection by-products in the food supply pose human health risks (Slattery & Garvey, 2025). Chlorate inhibits iodine uptake in humans (EFSA, 2015). Chlorate and perchlorate have been linked to thyroid hormone synthesis inhibition (McCarthy et al., 2018). Infants and small children with iodine deficiencies are particularly at risk from chronic exposure (EFSA, 2015). Chlorates also forms methemoglobin (a form of hemoglobin that cannot carry oxygen) in the bloodstream, which can cause methemoglobinemia (EFSA, 2015).[6]

[6] Methemoglobinemia is a condition where people have insufficient oxygen in the bloodstream. While cases in adults are rare and some are congenital, the condition is more severe in infants, children, and pregnant women. Methemoglobinemia has been linked to miscarriages, stillbirths, and "blue baby" syndrome in live births. A complete literature review of methemoglobinemia's causes, morbidity, and mortality, and the connection to chlorine disinfection by-products is beyond the scope of this technical report.

Not all toxic disinfection by-products formed by chlorine products contain chlorine. Humic acid exposed to chlorine and hypochlorous acid disinfectants can also form benzene, aldehydes, alkanoic acids, carboxylic acids, and other non-halogenated disinfection by-products when the free chlorine breaks the chemical bonds in the organic matter (Mazhar et al., 2020; WHO, 2000). These are discussed further in *Focus Question #2*.

Disinfection by-product toxicity in animals

Trihalomethanes and other disinfection by-products from chlorination have deleterious effects on living organisms based on their cytotoxicity, mutagenicity, and carcinogenicity (de Castro Medeiros et al., 2019; Liu et al., 2018). disinfection by-products have undergone extensive studies for genotoxicity, carcinogenicity, and mutagenicity (Cortés & Marcos, 2018; IARC, 1991; Mazhar et al., 2020; National Cancer Institute, 1976; Richardson et al., 2007). Most of the genotoxicity studies we found were based on isolated and cultured mammalian cell lines, with some models based on nematodes (*Caenorhabditis elegans*), zebrafish (*Danio rerio*), onions (*Allium sativa*), and fava beans (*Vicia faba*) (Cortés & Marcos, 2018). These studies consistently found that many disinfection by-products are carcinogens, mutagens, and cytotoxic (Cortés & Marcos, 2018; Richardson et al., 2007). Disinfection by-products vary in their toxicity by both their form and the target organism (Cortés & Marcos, 2018). Exposure routes also appear to be a factor in cytotoxicity and carcinogenicity (Mazhar et al., 2020). The research is ongoing as new disinfection by-products continue to be discovered.

Many researchers suggest that disinfection by-products function as endocrine-disrupting chemicals and influence hormone levels in exposed mammals (Chen et al., 2024; Sui et al., 2022).

Researchers reviewed 32 studies on the endocrine disruption effects of disinfection by-products published between 2000 and 2022 (Sui et al., 2022). The reports included 131 disinfection by-products that were tested on 14 endocrine-related targets consisting mostly of laboratory isolated receptors of specific hormones generated by endocrine glands. If disinfection by-products react with these targets in a destructive way, they are considered endocrine disruptors. The review grouped the disinfection by-products into eight subgroups and four classes to identify which might have the greatest endocrine disrupting potential. At least four subgroups showed disruptive activity on endocrine targets (Sui et al., 2022).

In another experiment, mice were fed two haloacetic acids: dichloroacetic acid and trichloroacetic acid. Researchers found that the haloacetic acids reduced testosterone, progesterone, and estradiol in mice exposed to them (Chen et al., 2024). The highest dose was 200,000 times the lowest dose. Pregnant mice that were exposed to haloacetic acids at 10^4-fold (10,000 times the lowest dose) had a significantly higher level of miscarriages than the control group. Pregnant mice exposed to 1,000 times the lowest dose for dichloroacetic acid (1.32 g/kg/d) and 100 times the lowest dose for trichloroacetic acid (2.64 g/kg/d) also had significantly more miscarriages. Both male and female mice had symptoms of endocrine disruption at 10^2-fold (100 times the lowest) doses (Chen et al., 2024).

In addition to creating endocrine disruptors, disinfection by-products will also react with various endocrine-disrupting compounds known to contaminate wastewater systems (Cochran et al., 2024). One laboratory study chlorinated the known endocrine disruptors 17β-estradiol, estrone, 17α-ethinylestradiol, bisphenol A (BPA), diclofenac, p-nonylphenol, and triclosan in ultrapure water and measured their endocrine disruptive capacity. Results varied for the different compounds. Chlorination significantly reduced the estrogenicity[7] of 17β-estradiol and estrone. However, the chlorinated hormones showed higher cytotoxicity. Chlorination reduced BPA's cytotoxicity. For several of the compounds, chlorination had no significant effect. Another experiment in the same study simulated the formation of endocrine disrupting compounds in wastewater and the reaction products of chlorine with known endocrine disruptors, with inconclusive preliminary results. The results of this second experiment have not been replicated on a large scale and the health impacts require further study (Cochran et al., 2024).

Haloacetonitriles (another family of disinfection by-products) showed possible mutagenic and carcinogenic properties on microbial and vertebrate animals (Bull et al., 1985). Simulation of exposure to haloacetonitriles using a computerized model (physiologically based pharmacokinetic model) showed that they had a high probability to cause non-carcinogenic health risks, including liver and kidney damage (Y. Zhang, Han, et al., 2018). However, the results have not been experimentally validated.

(C) Describe whether and how this substance and/or the breakdown products are persistent or cumulative when used in organic crop or livestock production, as petitioned.

Chlorine in water is unstable because it is a strong oxidizer (Chanda & Mehendale, 2005). However, reactive chlorine can bond with various organic molecules to form disinfection by-products that persist in the environment

[7] Estrogenicity is the potential of a substance to mimic or interfere with the effects of estrogen, a hormone.

(Anand & Mehendale, 2005). Filtration with granular activated carbon can significantly lower disinfection by-products from chlorinated wastewater before it is released or reclaimed (Verdugo et al., 2020).

The persistence of trihalomethanes and other disinfection by-products in water varies widely according to the molecular structure, temperature, pH, and total organic carbon (Pavelic et al., 2005). Persistence is measured by the time that 50% of a substance degrades (Pavelic et al., 2005). Chloroform has longer half-life than most trihalomethanes (Pavelic et al., 2005). As the first trihalomethane discovered, its environmental fate has been extensively studied (ATSDR, 2024). For example, the half-life of chloroform can range between minutes and months in the environment depending on conditions (ATSDR, 2024). Chloroform in surface water is expected to volatilize rapidly (ATSDR, 2024). Researchers found that chloroform under different conditions had a half-life of between 18 minutes and 44 days (ATSDR, 2024). The half-life depended on whether water was moving or still, and whether the chloroform was at the surface or submerged in solution. Chloroform in groundwater has a half-life of about two weeks (Pavelic et al., 2005). The half-life of chloroform in the soil under laboratory conditions at 25° C (77°F) is estimated to be 4.1 days (Anderson et al., 1991). Trihalomethane persistence in soil is also a function of the persistence of precursors in the form of organic matter (Eckard et al., 2020).

Chlorine can create disinfection by-products in food crops

Chlorate, trihalomethanes, and other disinfection by-products have been found in foods treated or grown with chlorinated water (Simpson & Mitch, 2022). Researchers tested samples of salads and spinach (Cardador & Gallego, 2012), ready-to-eat lettuce mixes (Bao Loan et al., 2016), and packaged chopped and shredded vegetables (Coroneo et al., 2017) purchased in European retail settings and found that all samples tested positive for various chlorination disinfection by-products (Simpson & Mitch, 2022). Gómez-López et al. (2013) found that replication of post-harvest handling conditions produced detectable levels of trihalomethanes in baby spinach. In another study, Komaki et al. (2018) found that replicated post-harvest handling conditions also created detectable levels of disinfection by-products produced by the reaction of the amino acid tyrosine and available chlorine—known as chlorotyrosines—in lettuce and spinach (Komaki et al., 2018). Researchers also discovered a chlorotyrosine compound in lettuce mix sold commercially (Bao Loan et al., 2016).

Tudela, López-Gálvez, Allende, & Gil (2019) found that experimental conditions replicated detectable levels of chlorates in fresh cut lettuce, shredded vegetables, and baby leaf lettuce. They also noted that commercial conditions are difficult to replicate because of the high variability in both the physiochemical and microbiological characteristics that commercial packinghouses encounter. Other disinfection by-products were not analyzed in the study because of the complexity involved in designing an experiment. The researchers concluded that results from different commercial operations will depend on the type of product, design of the equipment, and type of sanitizer. Empirical evidence for consumer exposure and other risks related to chlorination disinfection by-products requires sampling and analysis under commercial conditions (Tudela, López-Gálvez, Allende, & Gil, 2019).

Lonigro et al. (2017) grew lettuce in different soil types in greenhouse conditions and irrigated with sodium hypochlorite. The free chlorine levels were 0, 0.2, 10, and 40 mg/L. Extractable organic halogen levels in the lettuce increased with the concentration of available chlorine. The authors used extractable organic halogen because this fraction of organo-halides had the greatest mobility and was assumed to pose the greatest hazard. The increase in extractable organic halogen accumulation in the lettuce was greater when grown on silty-clay soils than on sandy soils. Silty-clay soils showed a significant difference in extractable organic halogen levels between the treated and untreated water at the lowest dose (Lonigro et al., 2017).

In another experiment, researchers found that field-grown baby spinach irrigated with water treated with chlorine dioxide showed elevated levels of chlorates compared with a field treated with unirrigated water (López-Gálvez et al., 2018). Lettuce grown under field conditions and irrigated with chlorinated reclaimed water also accumulated higher levels of chlorates than lettuce grown without chlorinated irrigation water (Garrido et al., 2020).

Disinfection by-products can accumulate in lipids

Chlorine disinfection by-products from sanitizing and disinfecting practices enter the milk supply (Nobile et al., 2022; Twomey et al., 2024). Disinfection by-products will accumulate in fat-rich foods, including dairy products such as whole milk and butter (Ryan et al., 2012). As such, disinfection by-products resulting from chlorine products used to sanitize bulk milk tanks, clean-in-place systems, and other dairy farm and dairy processing facility equipment are a public health concern (Gleeson et al., 2022; McCarthy et al., 2018; Twomey et al., 2024). The FDA's Pasteurized Milk Ordinance (PMO) does not set maximum levels of trihalomethanes, chlorates, perchlorates, or other potential disinfection by-products that may be present in the U.S. milk supply (FDA, 2023a).

Researchers in Europe analyzed baby food made from meat, fish, cheese, vegetables, and fruit for detectable levels of chlorate and perchlorate (Panseri et al., 2020). The fruit and vegetable samples had the highest levels. The researchers could not determine the origin of the contamination. They concluded that the most likely sources were either chlorine disinfected wastewater used for irrigation or post-harvest washing of the fruits and vegetables (Panseri et al., 2020).

No evidence that chlorine from chiller water creates disinfection by-products in poultry

In one experiment, researchers compared the levels of chloroform in chlorinated poultry carcasses (Robinson et al., 1981). Eviscerated poultry carcasses were treated with chlorine at levels between 5-50 mg/L. The meat was analyzed for chloroform. The control treatments had no detectable chloroform at micrograms per kilogram (µg/kg) concentrations in the tissue. The results on the chlorinated carcasses were reported to be "relatively low" but quantifiable in the 41-640 µg/L range. A dose of 50 mg/L resulted in a 640 µg/L concentration (Robinson et al., 1981). A more recent study reported that poultry treated with chlorine resulted in no detected trihalomethanes in poultry tissue at treatment levels below 70 mg/L of chlorine and were detected at levels below the limit of quantification in poultry tissue exposed to 70 and 100 mg/L of chlorine (Vizzier-Thaxton et al., 2010).

Environment and Human Health Effects

Evaluation Question #6: Discuss the effects of this substance on biological and chemical interactions in the agroecosystem. Include the physiological effects of this substance on soil, crops, livestock, or other organisms (such as aquatic) that could be affected by this substance when used as petitioned [7 U.S.C. 6518(m)(5)].

The biological and chemical interactions of chlorine within the agroecosystem can take place in crop or livestock production, as well as post-harvest handling. Chlorine products used as sanitizers and disinfectants in crop and livestock production and post-harvest handling and their disinfection by-products can have an impact on soil organisms and the agroecosystem (Asadollahi et al., 2025; Song et al., 2019).

Most studies on chlorine disinfection's adverse effects on the environment have focused on drinking water and wastewater treatment. We found fewer studies regarding the use of chlorine products for crop and livestock production. While some of those studies focused on organic farming systems, many did not. The general principles of disinfection by-products formation are described in *Evaluation Question #3*.

As we noted in *Action of the Substance*, the different species of chlorine are characterized by their chemical properties, particularly their oxidation state (Schmittinger et al., 2011). Chloride anions gain a single electron to complete its outermost atomic shell, and as a result they have an oxidation state of -1 (Haas, 2020; Schmittinger et al., 2011). Oxygenated chlorine's oxidation states can be formed by sharing electrons as hypochlorous acid and hypochlorite (+1), chlorites (+3); chlorates (+5), or perchlorates (+7) (Haas, 2020; Schmittinger et al., 2011).

While previously in this report we have primarily focused on available chlorine, here we include chloride as well because it can be important in the agroecosystem, even when fully reduced. For more information on chloride, refer to the 2023 technical report, *Potassium Chloride (Crops)* (NOP, 2023). Chloride is relatively non-reactive as a result of its -1 oxidation state (Haas, 2020). All living organisms metabolize sodium chloride (Feldman, 2005). Chloride is necessary for plant growth (Heckman, 2016). Sodium chloride—common table salt—plays key metabolic functions in animals in the control of water metabolism, regulating acid-base equilibrium, and maintaining osmotic pressure (Underwood & Suttle, 2010). Chloride deficiencies rarely arise in plants (Francis et al., 2023). While chloride *salt* is an essential plant nutrient, it can be toxic in excess (Geilfus, 2018; Heckman, 2016; Mall et al., 2021).

The effect of elevated chloride levels in plants varies by species (Geilfus, 2018; Heckman, 2016). Plants not adapted to growing in saline soils—known as halophytes—are more likely to be disturbed by excessive chloride at very low levels (Geilfus, 2018). Symptoms of excessive chlorine include premature yellowing of older leaves, burning of leaf margins and tips, and leaf abscission (Mall et al., 2021). Even at levels where symptoms are not visible, some sensitive crops may suffer from chlorine-related abiotic stress that will reduce growth and yields (Geilfus, 2018).

Chlorite, hypochlorite, and chlorine dioxide are highly reactive and toxic at a cellular level (Gallandat et al., 2021). Available chlorine is toxic to all forms of aquatic life (Chanda & Mehendale, 2005). Hypochlorous acid is often referred to as the most active form of chlorine and considered to have the greatest biocidal properties (Marriott et al., 2018). These compounds are not stable and quickly form a variety of disinfection by-products (Anand & Mehendale, 2005; Cai, 2005; Chanda & Mehendale, 2005). The environmental impacts caused by chlorine's biocidal properties are discussed further in *Evaluation Question #7*.

Crop production

Chloride

Researchers found that irrigation water chlorinated with sodium hypochlorite (10 and 40 mg/L of available Cl_2) caused symptoms of salinity stress in lettuce plants, including chlorosis, leaf necrosis, and reduced crop yields, particularly in treatments on sandy soils (Lonigro et al., 2017). Lettuce plants grown in sandy soil at the highest treatment levels were not viable for harvest because of the extent of these symptoms (Lonigro et al., 2017). Irrigation water sources with chlorine that was within the drinking water limit caused phytotoxicity to "Rex" lettuce (*Lactuca sativa*) (McGehee & Raudales, 2023).

Hypochlorous acid

Plants can be damaged by chlorine gas (Cl_2) (Maynard & Hochmuth, 1997) released by the reaction of hypochlorous acid (HOCl) with poultry manure (Bejan et al., 2013). Injuries include foliar necrosis and bleaching (Maynard & Hochmuth, 1997). Mustard, sweet corn, onions, and radishes are particularly sensitive to chlorine gas (Maynard & Hochmuth, 1997).

Researchers treated food waste used to make vermicompost with hypochlorous acid for odor control (C. Kim et al., 2019). Twenty earthworms (*Eisenia fetida*) were put in two separate bins. One bin with food waste was a control without additional treatment, and the other bin with food waste was treated with hypochlorous acid at a rate of 40-50 ppm prior to introducing the earthworms. The hypochlorous acid reduced ammonia (NH_3) concentrations by 40% and amine concentrations by 80% in the food waste. The reduction of these substances also measurably reduced odor. Earthworm populations in the treated food waste bin increased in both population size (29%) and total weight (92%) when compared to the control (C. Kim et al., 2019).

Disinfection by-products

In one experiment, soil exposed to chlorine disinfectants showed elevated levels of trihalomethane compounds and other disinfection by-products (Asadollahi et al., 2025). Both the chlorine dosage rate and duration of exposure were positively related to trihalomethane formation. Trihalomethane concentrations in the soil increased as the temperature increased from 22 °C to 30 °C (72 °F to 86 °F). The authors stated that the environmental factors of seasonality and temperature required further study (Asadollahi et al., 2025).

Researchers at an experiment station in southeastern China managed a rice paddy fertilized with four different rates of swine manure (Y. Zhang, Liang, et al., 2018). The researchers collected the paddy floodwater and added chlorine at drinking water concentrations of 3 mg/L to measure residual disinfection by-products precursors. They analyzed the water for dissolved organic carbon, trihalomethanes, and haloacetic acids. Dissolved organic carbon was assumed to be a proxy for disinfection by-products *precursors*. Dissolved organic carbon and disinfection by-products (trihalomethanes and haloacetic acids) were positively correlated with manure application rates. However, the levels of dissolved organic carbon and disinfection by-products diminished rapidly over the growing season. The authors concluded that the release of disinfection by-products in manure fertilized rice paddies could be minimized by improved irrigation management, controlling the floodwater below the ridges (checks), and by timing manure applications to reduce runoff from rainfall events (Y. Zhang, Liang, et al., 2018).

Livestock production

Animal drinking water treatments

In one study, researchers evaluated the effects of chlorinated drinking water on bull cattle (Llonch et al., 2023). The researchers provided bulls with either water treated with sodium hypochlorite acidified with phosphoric acid, or with untreated water.[8] All of the bulls consumed the same amount of water, and digested feed at a similar rate. While some disinfection by-products were found in the blood, they were below the reference dose. The researchers concluded that feed performance and carcass quality were significantly better in the bulls fattened with chlorinated water than the untreated control. This was attributed to improved microbiological water quality (Llonch et al., 2023).

Beekeepers use chlorine products to disinfect beehives and other apicultural equipment to prevent honeybee (*Apis mellifera*) diseases such as American foulbrood (*Paenibacillus larvae*). Honey bees fed water treated with chlorine dioxide with 10 and 100 ppm available chlorine experienced lower mortality and significantly longer lifespans than the untreated control (Lackett et al., 1972). However, exposure to 1,000 and 10,000 ppm of available chlorine caused 100% mortality by the fourth and second weeks, respectively, in the treated broods (Lackett et al., 1972).

Sodium chlorite, acidified teat dips

In one study, researchers found that acidified sodium chlorite teat dips applied pre- and post-milking prevented bacterial infections linked to mastitis comparable in efficacy to iodophors (Hillerton et al., 2007). However, the study only compared iodophore treatment to acidified sodium chlorite treatment. In other words, there was no non-treatment control, so the overall effectiveness of acidified sodium chlorite was not evaluated. We were unable to find other publicly available peer-reviewed studies that directly demonstrated the effectiveness of acidified sodium chlorite compared to a non-treatment control.

[8] Acidified sodium chlorite ($NaClO_2$) is not the same thing as a sodium hypochlorite (NaClO) solution with an added acid.

<u>Poultry house disinfectants</u>

Hypochlorite used to disinfect poultry houses reacts with free ammonia (NH_3) in poultry manure (Bejan et al., 2013). While treating poultry houses with hypochlorite is effective at reducing the ammonia and off-gases atmospheric nitrogen (N_2), the practice also releases chlorine gas (see *Equation 6*). Chlorine gas can be harmful to both birds and workers and lowers the pH of the cleaning water by the replacement of ammonia with H^+ (Bejan et al., 2013).

$$3\,HOCl + 2\,NH_3 \rightarrow N_2 + 3H_2O + 3H^+ + 3Cl^- \qquad \textit{Equation 6}$$

(Hypochlorous acid) + (Ammonia) → (Nitrogen gas) + (Water) + (Hydrogen cation) + (Chlorine anion)

Hypochlorous acid can react with ammonia to create nitrates (NO_3), chlorine gas, and acid (see *Equation 7*) (Bejan et al., 2013). Nitrate can be a pollutant (Bejan et al., 2013).

$$NH_3 + 4\,HOCl \rightarrow NO_3^- + 4Cl^- + 5H^+ + H_2O \qquad \textit{Equation 7}$$

(Ammonia) + (Hypochlorous acid) → (Nitrate ion) + (Chlorine anion) + (Hydrogen cation) + (Water)

Despite the disadvantages of requiring pH adjustment, toxicity to farm workers, and calcium deposits that form when calcium hypochlorite is used, hypochlorite is regarded by many researchers as the best available technology for ammonia control in poultry houses (Bejan et al., 2013).

<u>*Post-harvest handling*</u>

One study involved lettuce (*Lactuca sativa*) washed with water treated with different concentrations of sodium hypochlorite and pH regulators, including citric acid (Marín et al., 2020). The researchers measured trihalomethanes, haloacetic acids, and chlorine gas generated. disinfection by-products and chlorine gas were positively correlated with available chlorine concentrations. Citric acid significantly reduced disinfection by-products in the water and increased the amount of chlorine gas released. The researchers concluded that acidification lowers the risk of water contamination by disinfection by-products. The practice increased worker exposure to chlorine inhalation risks (Marín et al., 2020).

Evaluation Question #7: Discuss and summarize findings on whether the use of this substance may be harmful to the environment [7 U.S.C. 6517(c)(1)(A)(i) and 7 U.S.C. 6517(c)(2)(A)(i)].

According to several authors, most of the research on adverse impacts of chlorine materials on the environment is on trihalomethanes and other disinfection by-products of toxicological concern (Barrett et al., 2000; Bond et al., 2012; Rook, 1977; Simpson & Mitch, 2022; WHO, 2000).

The release of chlorine into the environment is known to form toxic disinfection by-products that include trihalomethanes and other carcinogenic products (Barrett et al., 2000; Bond et al., 2012; Murrell et al., 2021). Most disinfection by-products are categorized as organohalogens (Breider & Albers, 2015). While naturally occurring organohalogens are formed in minuscule amounts, most are considered anthropogenic toxic pollutants (Breider & Albers, 2015; Huber et al., 2009). Trihalomethane formation is a function of natural organic matter and available chlorine (Bond et al., 2012; Nikolaou & Lekkas, 2001). Chloroform and other disinfection by-products are readily formed by the reaction of chlorine with benzene ring structures extracted from humic acids (De Leer et al., 1985). Water pH and temperature may be a factor (Scarlat et al., 2025). Empirical studies about the effect of pH are mixed (Bond et al., 2012). Temperature appears to be a factor, with trihalomethane generation being greater during hot summer months (Dyck et al., 2015; Scarlat et al., 2025; Villanueva et al., 2007). However, this may be the result of elevated levels of organic matter and increased use of chlorine rather than higher temperatures (Dyck et al., 2015).

Chlorine disinfection alone significantly changes microfauna habitat, community structure, and the diversity of species throughout the food chain (Zhong et al., 2025). Specifically, wastewater in Wuhan, China was disinfected with chlorine and grown in lab conditions along with an untreated control. Researchers found that the protozoan microfauna, including amoebas, filter feeding ciliates, and flagellates were significantly reduced. Free living ciliates had higher counts in the chlorinated wastewater. The reduction in number of protozoa both as predators of bacteria and food for micro-metazoan species had implications for the ecological community. While bacteria were also killed by chlorination, their numbers increased more rapidly than protozoans in the absence of predation. Micro-metazoans that feed on protozoa, such as *Vorticella*, had decreased population growth compared with the untreated control. The researchers concluded that chlorination of wastewater has ecological implications throughout the aquatic biological community (Zhong et al., 2025).

Reactive chlorine species have efficacy across a broad range of species because of their broad cytotoxic nature (Gray et al., 2013). The mechanisms that make chlorine products effective disinfectants against pathogens also work against non-target beneficial microbial species. Reactive chlorine species kill microbes by several mechanisms that cause cell death including (Gray et al., 2013):

- oxidative stress
- loss of DNA replication ability
- enzymatic disruptions
- changes in sulfur-bearing amino acid (cysteine and methionine) metabolism
- loss of defenses to reactive metals
- changes in the cell envelope
- changes in the carbon metabolism

Researchers have observed that bacteria have stress response systems to counteract the toxic effects of reactive chlorine species. These may account for reactive chlorine species resistance of some target species, specifically *E. coli* (Gray et al., 2013).

In one experiment with corn, researchers treated drip irrigation with sodium hypochlorite at concentration levels of 0, 1.25, 2.5, and 5ppm for durations that varied at 0, 2, 1, and 0.5 hours respectively (Song et al., 2019). Chlorine used for the treatment of reclaimed wastewater and irrigation water reduced populations of non-target beneficial microorganisms responsible for soil health. Total bacteria, total fungi, and total actinomycetes all decreased in a linear relationship to the concentration of chlorine in the irrigation water, with the highest concentration of chlorine reducing bacteria populations 47.3%. The researchers also measured the activity of three bacterial enzymes in the soil:

- urease (responsible for the breakdown of organic forms of nitrogen into plant available ammonia)
- phosphatase (a soil enzyme critical for plant phosphorous uptake)
- catalase (an oxygen scavenger)

Enzymatic activity decreased for all three enzymes, presumably because of lower microbial populations to produce them (Song et al., 2019).

A laboratory experiment treated soil samples with a sodium hypochlorite solution and a hypochlorous acid solution to measure soil enzyme activity (L. Hua et al., 2024). Soil samples were treated with commercial disinfectants with low concentrations of 250 mg/L and high concentrations of 500 mg/L of each of the active ingredients. The researchers measured trihalomethanes after 24 hours. Hypochlorous acid generated higher levels of trihalomethanes with trichloromethane being the predominant disinfection by-products. Urease, phosphatase, catalase, and sucrase activity were measured at 7 days and 28 days. Phosphatase showed decreased activity with all treatments. Catalase, which is an oxygen scavenger, increased its activity. Urease activity decreased with the sodium hypochlorite treatments but increased with the low hypochlorous acid treatment. Plant available nitrogen in the form of ammonia is produced by urease activity. Sucrase activity was unchanged (L. Hua et al., 2024).

Necessity and Alternatives

Evaluation Question #9: Describe all natural (nonsynthetic) substances or products which may be used in place of this substance [7 U.S.C. 6517(c)(1)(A)(ii)]. Provide a list of allowed substances that may be used in place of this substance [7 U.S.C. 6518(m)(6)].

A summary of the alternatives to various chlorine materials is presented in *Table 6*. The table includes alternatives for all uses allowed for chlorine in each scope. Natural alternatives that are not on the nonsynthetic list of substances prohibited for production (§ 205.602 for crop production and § 205.604 for livestock production) are considered in Evaluation Question #9. Physical, mechanical, and other non-chemical methods for all three scopes considered in Evaluation Question #10. Alternatives are on the National List of Synthetic Substances Allowed for Production (§ 205.601 for crop production and § 205.603 for livestock production) and substances on the National List of Substances Allowed for Processing and Handling (§ 205.605) are also included for completeness.

The alternatives described in *Table 6* and the following pages are not exhaustive and do not cover all possible applications. Some may require validation of suitable efficacy by the operator through a Hazard Analysis Critical Control Point (HACCP) plan or additional data to meet food safety requirements and buyer specifications, in addition to compliance with organic standards. For some alternatives, additional research or regulatory action may be required before it can be substituted for chlorine. The Organic Materials Review Institute (OMRI) lists many formulated disinfectants and pesticide products that contain the alternatives listed in the following pages (OMRI, 2025). These can be found in a variety of OMRI classes and categories, for example:

- Crop Management Tools and Production Aids
    - Water Treatments
    - Acetic Acid
    - Drip Irrigation Cleaners

  - Peracetic Acid/Peroxyacetic Acid
  - Hydrogen Peroxide
- Livestock Management Tools and Production Aids
  - Hydrogen Peroxide
- Livestock Health Care
  - Botanicals
  - Essential Oils
  - Herbal Preparations
  - Cleaning Agents
- Processing Sanitizers and Cleaners
  - Bacteriophages
  - Fruit and Vegetable Wash, post-harvest
  - Citric Acid
  - Peracetic Acid/Peroxyacetic Acid
  - Peracetic Acid/Peroxyacetic Acid, post-harvest

Table 6:Alternatives to chlorine used in organic production and handling. *The table includes nonsynthetic substances allowed for crop and livestock use (and in some cases handling), as well as allowed synthetic substances that appear on the National List.*

Alternatives (NOP Citation)	**Scope/Use*/Sources**
Nonsynthetic/natural	
Biological controls, including bacteriophages (§ 205.105)	**Crops:** irrigation water treatment (Raudales et al., 2014); wastewater treatment (EPA, 2012). **Post-harvest handling:** food contact surfaces (Rivera-Lopez et al., 2025); fruit and vegetables (Meireles et al., 2016); carcass disinfection (Chaudhary et al., 2024); shell egg disinfection (Chaudhary et al., 2024).
Essential oils (§ 205.105)	**Livestock:** honey production (Hýbl et al., 2021); livestock drinking water disinfection (Galiş et al., 2013; Johny et al., 2008); teat dips (Aiemsaard et al., 2023; Caneschi et al., 2023; de Baïracli Levy, 1976; Karreman, 2004; Lopes et al., 2020). **Post-harvest handling:** food contact surfaces (Falcó et al., 2019); fruits and vegetables (Meireles et al., 2016).
Carboxylic acids (*e.g.,* citric, lactic) [§§ 205.105, 205.605(a)(1)]	**Crops:** irrigation water systems treatment (Zhangzhong et al., 2024). **Livestock:** livestock drinking water treatment (Galiş et al., 2013); honey production (Bojanic Rasovic, 2021). **Handling:** fruit and vegetables (Fatica & Schneider, 2009; Feliziani et al., 2016); carcass disinfection (Duan et al., 2017; Yoder et al., 2012).
Alcohol (nonsynthetic from natural fermentation) (§ 205.105)	**Post-harvest handling:** Fruits and vegetables (Suslow, 2000); food contact surfaces, equipment & machinery (Marriott et al., 2018; Silva, 2009).
Synthetic	
Alcohols: Ethanol, Isopropanol [§§ 205.601(a)(1), 205.603(a)(1)]	**Crops:** irrigation water systems treatment (Simonne et al., 2008); farm tools, equipment and machinery (Gauthier et al., 2020; Weicherding, 2006). **Livestock:** equipment (*e.g.,* surgical instruments) (Addie, 2024); teat dips (Wattenburger et al., 2020); honey production (Bojanic Rasovic, 2021).
Copper products [§§ 205.601(i)(2), 205.601(i)(3)]	**Crops:** farm tools, equipment & machinery (Weicherding, 2006); irrigation water treatment (chemigation) to prevent bacterial and fungal pathogens (Raudales et al., 2014).
Iodine [§ 205.603(a)(16)]	**Livestock:** barns, facilities, feeders (Jacob, 2013); drinking water treatment (HACCO, 2016; Preserve International, 2016); teat dips (Tikofsky, 2013).
Ozone [§§ 205.601(a)(5), 205.605(b)(21)]	**Crops:** irrigation water systems cleaner (Raudales et al., 2014; Simonne et al., 2008); wastewater treatment (EPA, 2012). **Post-harvest handling:** fruit and vegetable treatment (Fatica & Schneider, 2009; Silva, 2009). **Handling:** carcass disinfection (Pohlman, 2012); poultry chiller water (Pohlman, 2012).
Peroxy compounds (hydrogen peroxide; peracetic acid; sodium carbonate peroxyhydrate) [§§ 205.601(a)(4), 205.601(a)(6) 205.601(a)(8), 205.601(i)(5), 205.601(i)(8), 205.603(a)(15), 205.603(a)(24), 205.605(b)(17), 205.605(b)(22)]	**Crops:** irrigation water systems treatment (Biosafe, 2017; Raudales et al., 2014); farm tools, equipment, and machinery (Biosafe, 2022). **Livestock:** barns, facilities, feeders (Jacob, 2013; Sigurdson et al., 2004); livestock drinking water treatment (EnviroTech Chemical Services, 2024); equipment in contact with raw fluid milk (Biosafe, 2017; NYSCHAP, 2025a); shell egg disinfection (Ecolab, 2025; Negrete, 2014); teat dips (Leslie et al., 2006); honey production (Bojanic Rasovic, 2021). **Handling:** food contact surfaces, equipment and facilities (Biosafe, 2017; Ecolab, 2025; Marriott et al., 2018; Silva, 2009); fruit and vegetables (Biosafe, 2017; Ecolab, 2025; Fatica & Schneider, 2009; Suslow, 2006).

**Note that all listed uses may not be approved for every pesticide product that claims the specified active ingredient. Some of the biologically based products may be produced using excluded methods.*

Various non-synthetic substances can be used as alternatives to chlorine in all scope for a wide variety of uses and applications. This technical review classifies them as biological controls, essential oils, and carboxylic acids from derived from natural sources. In addition, various synthetic substances allowed for organic production and handling may also be used in place of chlorine materials. These include alcohols, fixed coppers, copper sulfate, iodine, ozone, and peroxy compounds.

<u>Nonsynthetic alternatives</u>

<u>Biological controls</u>

Various microorganisms and naturally occurring biological products can replace chlorine for certain applications.

Crops

In one study, researchers introduced the beneficial bacteria *Bacillus amyloliquefaciens* as a broad-spectrum antagonist to inhibit the formation of biofilm producing algae and other organisms in reclaimed water used in irrigation lines (Wen et al., 2021). The simple experiment consisted of reclaimed wastewater treated with *Bacillus amyloliquefaciens* and an untreated control, replicated over various time periods. *Bacillus amyloliquefaciens* reduced biofilm by 37.2-89.4%, significantly reduced emitter clogging, and increased water flow from the emitters. Producers still had to unclog the treated irrigation lines, but less frequently than the untreated control (Wen et al., 2021).

Handling

Viruses that infect bacteria and other foodborne pathogens can be used to control specific target microorganisms, such as *Salmonella* spp. (O'Sullivan et al., 2019; S. Wei et al., 2019). These are commonly referred to as "bacteriophages" or simply "phages" (Marriott et al., 2018; O'Sullivan et al., 2019), and are specific to their host (Marriott et al., 2018). While some phages infect beneficial microorganisms used for fermentation, others are specific to foodborne pathogens (O'Sullivan et al., 2019). Host specificity is an advantage that phages have over broad-spectrum synthetic anti-microbials like chlorine dioxide (Chaudhary et al., 2024).

The FDA first approved phages for food use in 2006 (Rivera-Lopez et al., 2025). Phage products that are approved for food use include those that combat *Listeria, Salmonella,* and *E. coli* (Marriott et al., 2018). Companies that manufacture FDA-approved phages for the food industry include Intralytix (Columbia, MD), OmniLytics (Sandy, UT), Passport Food Safety Solutions (West Des Moines, IA), and Elanco (Greenfield, IN) (Rivera-Lopez et al., 2025).

Note that some phages may be genetically modified or made by methods otherwise excluded from organic production and handling [7 CFR 205.105(e)] (Chaudhary et al., 2024).

<u>Essential oils</u>

Aromatic oils extracted from plants are effective antimicrobial pesticides in various agricultural and food handling applications (Baker & Grant, 2018; Burt, 2004; Laranjo et al., 2017; Rawat, 2021). Known as essential oils, these botanical derivatives present viable alternatives to chlorine and other synthetic chemical disinfectants and sanitizers for certain applications (Baker & Grant, 2018; Burt, 2004).

Essential oils exempt from the requirement of registration with EPA as pesticides include [40 CFR 152.25(b)]:

- cinnamon
- clove
- geranium
- peppermint
- thyme
- wild thyme

The European Pharmacopoeia identifies 29 different essential oils with antimicrobial effects on fungi, yeast, and gram-positive and gram-negative bacteria (Pauli & Schilcher, 2009). These materials are characterized as weak-to-moderate antimicrobials with inconsistent activity across all targeted species of foodborne pathogens (Pauli & Schilcher, 2009; Wińska et al., 2019). Efficacy is generally a function of the concentration of the essential oils' active components, with higher concentrations being more effective (Wińska et al., 2019). Most essential oils are not comparable to chlorine in their biocidal activity (Meireles et al., 2016; Wińska et al., 2019).

Crops

In one study, researchers inoculated raw peppers with chlorine-resistant *Aeromonas* strains and treated them with thyme oil at 0.5% and 1.0% concentrations (Uyttendaele et al., 2004). The *Aeromonas* counts were below the limit of quantification at both doses (Uyttendaele et al., 2004).

Livestock

Essential oils are a natural alternative for dairy animal hygiene and can be used as teat dips or sprays to prevent and treat mastitis (Aiemsaard et al., 2023; Caneschi et al., 2023; Dal Pozzo et al., 2011; de Baïracli Levy, 1976; Karreman, 2004; Queiroga et al., 2018). Organic dairy farmers have used herbal substances to treat mastitis since the 1930s (de Baïracli Levy, 1976). Researchers reported that the following essential oils and their active constituents were effective inhibitors of mastitis agents *Staphylococcus* spp., *Streptococcus, E. coli, Candida* spp.*,* and other organisms that infect teats:

- artemisia (*Jasonia montana*) (Lopes et al., 2020)
- cinnamon (*Cinnamomum* spp.) (Caneschi et al., 2023; Lopes et al., 2020)
- clove (*Syzygium aromaticum*) (Lopes et al., 2020)
- copaiba (*Copaifera* spp.) (Lopes et al., 2020)
- garlic (*Allium sativum*) (Lopes et al., 2020)
- kokilaksha *(Asteracantha longifolia*) (Lopes et al., 2020)
- lavender (*Lavendulas* spp.) (Caneschi et al., 2023)
- lemongrass (*Cymbopogon citratus*) (Lopes et al., 2020)
- oregano (*Origanum vulgare*) (Caneschi et al., 2023)
- piperina (*Minthostachys verticillate*) (Caneschi et al., 2023; Lopes et al., 2020)
- pomegranate (*Punica granatum*) (Lopes et al., 2020)
- savory (*Satureja montana*) (Caneschi et al., 2023)
- shell ginger (*Alpinia zerumbet*) (Lopes et al., 2020)
- tea tree (*Melaleuca alternifolia*) (Caneschi et al., 2023)
- thyme (*Thymus vulgaris*) (Caneschi et al., 2023)
- thymol (active constituent of *Thymus* spp.) (Caneschi et al., 2023)
- wild thyme (*Thymus serpyllum*) (Caneschi et al., 2023)

Most of the mastitis-essential oil studies reviewed were conducted in laboratory conditions and not validated in field conditions (Caneschi et al., 2023; Lopes et al., 2020).

Researchers continue to test essential oils for their efficacy in preventing and treating mastitis in dairy animals (Aiemsaard et al., 2023; Munive Nuñez et al., 2024; Queiroga et al., 2018). Essential oils sold for human use in the U.S. are regulated under the Dietary Supplement Health and Education Act of 1994 (DSHEA) (P.L. 103-417, October 24, 1994). However, the FDA's opinion is that DSHEA does not apply to supplements used for animals, including food animals (FDA, 2025). As such, essential oils are unapproved (by the FDA) animal drugs that are allowed by FDA's discretion, similar to all other teat dips (FDA, 1995).

In another study, processors treated chicken drinking water infected with *Salmonella enteritidis (S. enteritidis)* and *Campylobacter jejuni (C. jejuni)* with trans-cinnamaldehyde, the natural active constituent of cinnamon oil (Johny et al., 2008). Trans-cinnamaldehyde at concentrations above 0.03% reduced *C. jejuni* to undetectable levels after one day. A dose of 0.6% trans-cinnamaldehyde was required to completely inactivate *S. enteritidis* (Johny et al., 2008).

Researchers evaluated thirty different essential oils for their efficacy in the control of the honeybee (*Apis mellifera*) parasitic mite *Varroa destructor* (Hýbl et al., 2021). Varroa mites were isolated from honeybees and treated under laboratory conditions. The researchers found that the essential oils of the following plants were the most effective controls of Varroa mite (Hýbl et al., 2021):

- manuka (*Leptospermum scoparium*)
- thyme (*Thymus vulgaris*)
- wild thyme (*Thymus serpyllum*)
- thymol (active constituent of *Thymus* spp.)
- oregano (*Origanum vulgare*)
- savory (*Satureja montana*)
- cinnamon (*Cinnamomum zeylanicum*)
- clove (*Syzygium aromaticum*) bud
- peppermint (*Mentha piperita*)
- carrot (*Daucus carota*)
- geranium (*Pelargonium graveolens*)

- litsea (*Litsea cubeba*)

Handling

There are a few alternatives to chlorine materials that that researchers have investigated for specific foodborne pathogens (Burt, 2004). The most studied essential oil sources (and their active constituents) include (Burt, 2004):

- cinnamon (*Cinnamomum zeylandicum*) (cinnamaldehyde)
- clove (*Syzygium aromaticum*) (eugenol and eugenol acetate)
- coriander / cilantro (*Coriandrum sativum*) (linalool and E-2-decanal)
- oregano (*Origanum vulgare*) (carvacrol, thymol, γ-terpinene, p-cymene)
- rosemary (*Rosmarinus officinalis*) (α-pinene, bornyl acetate, camphor, 1,8-cineole)
- sage (*Salvia officinalis*) α- and ß-pinene, 1,8-cineole, α-tujone)
- thyme (*Thymus vulgaris*) (thymol, carvacrol, γ-terpinene, p-cymene)

Researchers have studied the antimicrobial effects of various essential oils on the following foodborne pathogens (Burt, 2004):

- *E. coli*
- *Listeria monocytogenes*
- *Salmonella typhimurium*
- *Shigella dysenteriae*
- *Staphylococcus aureus*
- *Bacillus cereus*

The authors of the 2025 technical report, *Ozone*, mention cinnamon oil, peppermint oil, and thyme oil as examples of potential organic alternatives to ozone disinfection (NOP, 2025c). These are all potential alternatives to chlorine for certain similar applications. The authors of the 2025 Ozone technical report also included a list of organic essential oil suppliers (NOP, 2025c).

Essential oils are not widely used on food contact surfaces, but researchers have explored their potential (Falcó et al., 2019). The researchers suggested further improvements and testing under different conditions to make essential oils a viable alternative to synthetic chemical sanitizers (Falcó et al., 2019).

Researchers have extensively studied plant extracts—including essential oils—as alternative disinfectants for the post-harvest handling of fresh fruits and vegetables (Meireles et al., 2016). Much of the research has explored their use as concentrated active constituents at known concentrations, given the variability that essential oils have in their active constituent content. Commercial use is limited because essential oils can change the organoleptic properties of fresh produce. They also need to be formulated in ways that achieve greater pathogen reduction for shorter contact times. Finally, the high cost has also been a deterrent to commercial use (Meireles et al., 2016).

Some of the more promising studies are included for reference. Post-harvest treatments with essential oils can inhibit the growth of organisms that can cause spoilage and food poisoning. Cut pineapple (*Ananas comosus*) coated with 0.3% lemongrass (*Cymbopogon citratus*) oil in an alginate-sunflower oil base had significantly lower populations of molds, yeasts, and aerobic bacteria than an untreated control, a control treated only with the alginate-sunflower oil coating, or a 0.1% concentration of lemongrass oil (Azarakhsh et al., 2014).

Researchers compared *E. coli* levels on infected lettuce and baby carrots that were washed in water disinfected with chlorine dioxide, ozone (O_3), and thyme oil, and a sequential combination of the three treatments with unwashed and deionized water control (N. Singh et al., 2002). The chlorine dioxide treatment was a dose of 10 mg/L for 10 minutes, ozone was 9.3 mg / L for 10 minutes and thyme oil was 1.0 mL / L for 5 minutes. All three treatments by themselves achieved less than a one-log reduction of pathogens in lettuce and were not significantly different from each other, and thyme oil was the most effective treatment for carrots by a small, but statistically significant difference (N. Singh et al., 2002). The results are discussed further in section *Ozone* below.

Carboxylic acids

Various naturally occurring acids, such as citric acid, lactic acid, and acetic acid, are known to have antimicrobial properties (Bermúdez-Aguirre & Barbosa-Cánovas, 2013; In et al., 2013; Mani-López et al., 2012; Ricke, 2003). Citric acid, produced by microbial fermentation of carbohydrate substances, and lactic acid are on the National List of nonagricultural nonorganic substances allowed as ingredients in or on processed products labeled as “organic” or “made with organic (specified ingredients or food groups)” [7 CFR 205.605(a)(1)]. For some applications (described below), citric acid performs poorly (Bermúdez-Aguirre & Barbosa-Cánovas, 2013; Cho & Ha, 2021).

Organic acids may reduce microbial activity by multiple modes of action that acidify the cytoplasm, making it toxic (Mani-López et al., 2012). The undissociated acids flow through the deformed cell structure and interfere with enzymatic activities, disrupt proteins and DNA structures, and ultimately damage extracellular membranes (In et al., 2013; Mani-López et al., 2012). Natural organic acids inhibit cell division and decrease viability by damaging the RNA and DNA (Mani-López et al., 2012). While the cells are not instantly destroyed, they are fatally injured (In et al., 2013).

Crops

Nonsynthetic acetic acid and citric acid can be used to clean drip irrigation equipment in organic farming systems (Simonne et al., 2008). Because they are weak acids, treatment may require larger doses than stronger synthetic acids used in conventional production, like hydrochloric acid, sulfuric acid, or phosphoric acid (Simonne et al., 2008). However, citric acid and other nonsynthetic acids displayed superior anti-fouling capacity in treating desalinated water compared with phosphoric and other synthetic inorganic acids (Zhangzhong et al., 2024).

Researchers have investigated carboxylic acids as alternative treatments to manage honeybee pathogens (Bojanic Rasovic, 2021). American foulbrood is the main target organism treated with chlorine in honey production systems (Lackett et al., 1972; Mahdi et al., 2022). However, formic acid, lactic acid, and oxalic acid are relatively ineffective in their antimicrobial activity against American foulbrood (Farghaly et al., 2023).

Handling

Various carboxylic acids have been widely studied as alternatives to chlorine for use in post-harvest handling of fresh fruits and vegetables. They have also been used to reduce foodborne pathogens in meat and poultry products.

Researchers prepared a microbial broth of four pathogenic *Shigella* species (*S. boydii, S. dysenteriae, S. flexnari,* and *S. sonnei*) and treated them with a mixture of citric acid, lactic acid, and acetic acid at a concentration of 0.5% (In et al., 2013). This treatment inhibited the growth of these microorganisms and reduced their populations in the broth by 1-2 logs. Lactic acid achieved a 5-log reduction of *S. sonnei* and a 2-log reduction of *S. boydii* after two hours. In the same study, the researchers inoculated lettuce with *Shigella* cultures and submerged them in water. Over a 10-hour period, the addition of a 0.5% solution of each of the three acids injured target organisms to reduce their viability (In et al., 2013). The most effective treatment against *S. dysenteriae* was acetic acid, with 100% injury after 8 hours. The other *Shigella* species were more susceptible to lactic acid (In et al., 2013).

Eliuz (2020) inoculated nutrient broths with *E. coli, S. aureus,* and *C. albicans* and treated them with citric acid. This method yielded a reduction in all three species, with *C. albicans* showing the greatest sensitivity to citric acid.

Cho and Ha (2021) inoculated spinach with *E. coli, S. typhimurium* and *L. monocytogenes* and treated the spinach with a 1% solution of citric acid, with pulsed broad-spectrum xenon light, and with the two treatments combined. The citric acid treatment alone achieved less than a one-log reduction of all three of the pathogens. Xenon light by itself achieved a 4-5 log reduction of the various target organisms with a 60-minute treatment time. A 60-minute treatment time using both xenon light and citric acid achieved greater than a six-log reduction for all three target pathogens (Cho & Ha, 2021).

Citric acid was the least effective disinfectant of *E. coli* on lettuce, tomatoes, and carrots when compared with chlorine, ozone, and UV light (Bermúdez-Aguirre & Barbosa-Cánovas, 2013). Citric acid treatments of 0.5%, 1.5%, and 3% resulted in no *E. coli* inactivation in carrots or lettuce after 15 minutes of treatment. Tomatoes had less than a 1-log reduction in the target organism when exposed at 3% for 15 minutes. The authors acknowledged that the low rate and short exposure time might have been a factor (Bermúdez-Aguirre & Barbosa-Cánovas, 2013).

Various *Aeromonas* species are foodborne pathogens that can cause diarrhea in adults and children (Uyttendaele et al., 2004). Some strains, such as *A. caviae* and *A. hydrophila* are resistant to chlorine. Researchers inoculated carrots with chlorine-resistant strains and treated them with lactic acid at a 2.0% concentration. The *Aeromonas* counts were below the limit of quantification when the treated carrots were stored at 4 °C, but the bacteria was able to recover at a storage temperature of 7 °C (Uyttendaele et al., 2004).

Yoder et al. (2012) compared treatments of beef infected with a fecal slurry pathogen cocktail containing *E. coli*, *Salmonella typhimurium, Campylobacter coli,* and *Campylobacter jejuni.* The treatments involved rinses with:

- acidified sodium chlorite (500 and 1,200 ppm)
- sodium hypochlorite (100 and 600 ppm)
- chlorine dioxide (100 and 540 ppm)
- peroxyacetic acid (100 and 200 ppm)
- ozone gas (15 and 30 seconds)
- acetic acid (1, 2, and 5%)

- citric acid (1, 2, and 5%)
- lactic acid (1, 2, and 5%)

The control in Yoder's study was a plain water rinse. The organic acid rinses effectively reduced bacterial loads in beef comparable to treatment with chlorine compounds. Lactic acid applied with hand-held equipment at a 2% solution was the most effective treatment as a carcass rinse for beef (Yoder et al., 2012).

In another study, researchers compared the effectiveness of disinfectants on chicken carcasses from both a fast-growing modern white-feathered breed raised in confinement for six weeks prior to slaughter and a slower growing traditional yellow-feathered breed that was raised for 12 weeks and provided outdoor access (Duan et al., 2017):

- sodium hypochlorite (50 and 100 mg/L)
- chlorine dioxide (50 and 100 mg/L)
- acid electrolyzed oxidizing water (30 mg/L and 58 mg/L)
- lactic acid (1% and 2%)

The chicken carcasses were sprayed and stored for 8 days at 4 °C (39 °F). Total viable count (TVC) and total coliforms count were taken every day. At the end of the experiment, the lactic acid treatment lowered counts compared to the untreated control and sterile water treatment and was not significantly different from the chlorinated treatments in reducing both TVC and total coliforms. However, the lactic acid treatment resulted in lipid oxidation, which causes meat quality deterioration and limits shelf life (Duan et al., 2017).

Nonsynthetic sources of carboxylic acids are widely available. Carboxylic acids can also be synthesized in some cases, requiring verification of the source and manufacturing process. Some sources are included in *Table 6*.

<u>*Synthetic Alternatives*</u>

In addition to the nonsynthetic biological controls, essential oils, and carboxylic acids, some synthetic substances allowed for use in organic production and handling can also be used as alternatives to chlorine. These include ethanol and isopropyl alcohol; fixed copper products; iodine; ozone; and the peroxy compounds hydrogen peroxide, peracetic acid, and sodium carbonate peroxyhydrate. These may be subject to limitations on their use based on the annotations on the National List.

<u>Alcohols</u>

Ethanol and isopropyl alcohol are allowed as disinfectants in both organic crop [7 CFR 205.601(a)(1)] and livestock [7 CFR 205.603(a)(1)] production.

Crops

In crop production, alcohols are viable alternatives to disinfect hand tools and equipment (Chalker-Scott, 2013; Weicherding, 2006). Alcohol is not corrosive to steel like chlorine products (Weicherding, 2006). A 70% alcohol solution for a 10-15 minute contact time is a practical way to disinfect tools (Gauthier et al., 2020).

Fireblight (*Erwinia amylovora*), a major pathogen of apples (*Malus domestica*), can be spread through infected tools used to prune trees during dormant season (Horner et al., 2024). Researchers infected pruning shears with fireblight colonies, then treated them with ethanol at 70%, 80%, and 95% and sodium hypochlorite at 0.068% and 0.135% solutions. Three essential oils (pine, lemon, and manuka) were also included along with other proprietary products that are not known to be allowed for organic production. The experiment was conducted over a three-year period. Ethanol at 80% concentration reduced the population to a comparable degree as sodium hypochlorite. However, it did not eliminate the pathogen from the pruning shears as completely as the highest concentration of available chlorine. The alcohol-treated pruning shears showed no corrosion, while the shears treated with effective levels of sodium hypochlorite were among the most corroded tools by the third year of the experiment (Horner et al., 2024).

Livestock

Alcohol is primarily used as a topical disinfectant on animals and to disinfect surgical equipment (Addie, 2024).

Some producers use single-use towels containing isopropyl alcohol as a teat wipe. This can be an effective pre-milking treatment to reduce bacteria associated with mastitis (Wattenburger et al., 2020). Veterinary researchers compared two pre-milking treatments: a single use 70% solution wipe used on the teat end and a 1% spray-on iodine solution. The researchers also applied a third treatment containing both iodine and alcohol as the pre-milking teat dip. After treatment, milk samples were analyzed for *Staphylococcus, Corynebacterium,* and other bacterial species of concern that cause mastitis and milk contamination. All treatments were effective in reducing bacterial counts with alcohol being more effective than iodine. The combination of iodine and alcohol was the most effective treatment (Wattenburger et al., 2020).

As an alternative treatment for beekeepers, alcohols act quickly and leave no residue (Bojanic Rasovic, 2021). However, they are volatile. Alcohol can damage rubber objects and dissolve glue (Bojanic Rasovic, 2021).

As of October 13, 2025, the EPA listed 718 registered products that contain ethanol as an active ingredient, and 161 containing isopropyl alcohol as an active ingredient (EPA, 2025c). Some are included in *Table 7* as certified by EPA's Design for the Environment program (EPA, 2025a), however these were not reviewed for compliance with the USDA organic regulations. Denatured ethyl alcohol and isopropyl alcohol are widely available as over-the-counter drugs. We reviewed the NIH DailyMed database on October 12, 2025 and found 18,610 products that listed alcohol on the label as the active ingredient (U.S. NLM, 2025a). None were specifically labeled as teat dips, but many were labeled for general use for topical disinfection, antiseptic, and bactericide on both humans and animals (U.S. NLM, 2025a).

Fixed coppers

Crops
Copper sulfate and the fixed copper fungicides copper hydroxide, copper oxide, copper oxychloride, and other copper products exempted from EPA tolerance appear on the National List for disease control in crops [7 CFR 205.601(i)(2) and (3)]. Pruning shears can be treated with a copper dip as an alternative to a chlorine dip (Chalker-Scott, 2013; Weicherding, 2006). Copper salts can also be used to treat irrigation water for waterborne plant pathogens such as *Phytophthera capsici* (Granke & Hausbeck, 2010). However, copper products may be used as an algicide in organic production only in rice production under limited conditions that does not include drip irrigation cleaning [§ 205.601(a)(3)].

Iodine

Livestock
Iodine is allowed as a disinfectant, sanitizer, and medical treatment for organic livestock without any annotative limitations placed on its use or its co-formulants [7 CFR 205.603(a)(16)]. Iodine is the dairy industry's most tested antimicrobial (Belsito, 2012). Iodine-based sanitizers are mixed with surfactants and the formulated products are called "iodophors" (Sigurdson et al., 2004). Iodine is used on organic farms as a teat dip and for udder care of milking dairy cows (Tikofsky, 2013). Iodine's efficacy as a post-milking teat disinfectant is comparable to acidified sodium chlorite (Hillerton et al., 2007). As noted above, researchers found pre-milking treatment with both iodine and alcohol to be more effective than iodine alone (Wattenburger et al., 2020).

Iodine is also labelled for use as a poultry drinking water disinfectant (Preserve International, 2016).

In one experiment, Turabekov et al. (2024) found that an iodine-based disinfectant reduced microorganism counts by over 70% in poultry houses after three hours of exposure.

Iodophors used in honey production have the advantage that they act quickly and are relatively non-toxic (Bojanic Rasovic, 2021). The disadvantages of iodine based disinfectants is that they are corrosive to metals and can cause tissue damage (Bojanic Rasovic, 2021).

As a halogen like chlorine, iodine will create trihalomethanes, haloacetic acids, and other disinfection by-products when combined with chlorination under laboratory conditions (Postigo et al., 2017).

In May 2025, the NOSB recommended that iodine products must be not be formulated with nonylphenol ethoxylates (NPEs) in (NOSB, 2025). As of September 9, 2025, OMRI had five iodine products listed as NPE-free (OMRI, 2025). As of September 9, 2025, the NOSB recommendation to prohibit NPEs had not been finalized by the NOP through rulemaking, though the USDA reported that they were reviewing the recommendation to determine next steps (NOP, 2025a).

Ozone
The authors of the 2025 technical report, *Ozone* (O_3), included a discussion of various nonsynthetic substances and alternative substances on the National List that can be used as antimicrobials (NOP, 2025c). Some are also included in this technical report, with an emphasis on their efficacy relative to chlorine.

Crops
For crop production use, the National List limits the use of ozone to pre-harvest use as an irrigation system cleaner [7 CFR 205.601(a)(5)]. Ozone is recognized as an alternative to chlorine for the treatment of wastewater (EPA, 1999, 2012). Most of the ozone applications take place during some part of tertiary treatment of wastewater before the water is released to the producer. Researchers found that injecting ozone into irrigation water can reduce many

different waterborne plant pathogens (Raudales et al., 2014). Plant pathogens shown to be reduced or eliminated by ozonation of irrigation water under experimental conditions include:

- *Acidovorax avenae* (Hopkins et al., 2009)
- *Fusarium oxysporum* (Kobayashi et al., 2011)
- *Pectobacterium carotovorum* (Kobayashi et al., 2011)

Livestock

Ozone can be used to disinfect and remove ammonia from poultry barns (Bejan et al., 2013). Ozone reacts with ammonia to form nitrate (NO_3^-), atmospheric oxygen, and water (see *Equation 8*). The reaction is similar to the reaction with hypochlorous acid in *Equation 7*, except that instead of releasing toxic chlorine gas, the ozone reaction releases non-toxic atmospheric oxygen.

$$NH_3 + 4\,O_3 \rightarrow NO_3^- + 4O_2 + H_2O + H^+ \qquad \textit{Equation 8}$$

(Ammonia) + (Ozone) → (Nitrate ion) + (Oxygen) + (Water) + (Hydrogen cation)

Like hypochlorite treatment, ozone also presents hazards to birds and humans that might inhale ozone gas or the gaseous by-products (Bejan et al., 2013).

Handling

In handling, ozone is allowed for use in or on processed products labelled as “organic” or “made with organic (specified ingredients or food groups)” [7 CFR 205.605(b)]. Prior to the establishment of the USDA organic regulations, ozone was recognized as a viable alternative to chlorine for many applications in organic food systems (NOP, 1995). Ozone has greater microbiological activity than chlorinated compounds (Khadre et al., 2001; J.-G. Kim et al., 2003). Ozone is effective at lower concentrations and shorter contact times than chlorine-based sanitizers (Ölmez & Kretzschmar, 2009). Ozone is most effective at a pH of 6.0-8.5 (Marriott et al., 2018). However, because of ozone’s instability and short-lived nature, ozone does not provide persistent disinfect residues the same way that chlorine does (J.-G. Kim et al., 2003).

In a study, Bermúdez-Aguirre and Barbosa-Cánovas (2013) inoculated romaine lettuce, grape tomatoes, and baby carrots with *E. coli*, then treated the produce with chlorine at 50, 100, and 200 ppm. The chlorine treatment was compared to vegetables treated with ozone (5 ppm), citric acid (0.5, 1, and 1.5%), and UV-light. They found that ozone achieved comparable results to chlorine in disinfecting tomatoes, but was less effective than chlorine for lettuce and carrots, and resulted in the discoloration of lettuce (Bermúdez-Aguirre & Barbosa-Cánovas, 2013).

Ozonation and chlorination are not mutually exclusive treatments (G. Hua & Reckhow, 2007). Pre-ozonation of water can reduce the amount of chlorine needed and thereby reduce the generation of trihalomethanes and other disinfection by-products (G. Hua & Reckhow, 2007). Wastewater that was pre-ozonated prior to chlorination had lower levels of disinfection by-products than pre-chlorinated wastewater, but the disinfection by-products in the pre-ozonated wastewater were more cytotoxic (Verdugo et al., 2020). Pretreatment produced fewer trihalomethanes, but more haloacetic acids, haloacetomides, and haloacetonitriles (Verdugo et al., 2020). Haloacetomides and haloacetonitriles are more cytotoxic than trihalomethanes, but are not regulated in drinking water (Verdugo et al., 2020).

As noted in *Essential Oils*, N. Singh et al. (2002) compared the efficacy of chlorine dioxide, ozone, and thyme oil as vegetable washwater disinfectants. The result of ozone treatment was not statistically different from the chlorine dioxide treatment in achieving less than a one-log reduction of *E. coli* on both lettuce and baby carrots. The most effective treatment was the sequential treatment of thyme oil, followed by ozone, then chlorine dioxide. The three sequential treatments reduced *E. coli* by 3.83 log in lettuce and 4.34 log in baby carrots (N. Singh et al., 2002).

Peroxy compounds

Crops

Hydrogen peroxide [7 CFR 205.601(a)(4)] and other peroxy compounds, such as peracetic acid [§ 205.601(1)(6)], have effective sanitizing properties for irrigation system cleaning (Raudales et al., 2014). A review article included reference to an efficacy report that found the combination of hydrogen peroxide and peracetic acid is 100% effective against the algae *Microcystic* spp., *Scenedemus* spp., and *Chlorococcum* spp. (Raudales et al., 2014). Hydrogen peroxide and peracetic acid are EPA approved for use to treat irrigation water, drip and other irrigation systems (Biosafe, 2017).

Vänninen and Koskula (1998) studied the effect of hydrogen peroxide on cucumbers (*Cucumis sativa*) grown in a greenhouse on a rockwool substrate. They found that two treatments during the growing season at levels of 975 and 1,500 ppm of hydrogen peroxide visibly reduced algal growth, but also scorched the leaves of the cucumbers

(Vänninen & Koskula, 1998). Reducing the dosage to 125 ppm and applying on a weekly basis inhibited algal growth and caused less phytotoxicity (Vänninen & Koskula, 1998).

Greenhouse containers, walls, floors, foot baths, and tools can be effectively disinfected by using either hydrogen peroxide by itself or in combination with peracetic acid (Gauthier et al., 2020). The recommended contact times are 1-10 minutes for hydrogen peroxide and 10-15 minutes for peracetic acid (Gauthier et al., 2020).

Peracetic acid can be applied to wastewater for disinfection, oxidation, and odor control (Freitas et al., 2021). Researchers in Brazil compared wastewater treated with sodium hypochlorite and PAA at different levels and contact times and compared *E. coli* and total coliform counts. The researchers also measured sulfide levels as a proxy for odor control. They determined that the best disinfection conditions were produced by a dose of 15 mg/L available disinfectant and a contact time of 15 minutes for both disinfectants. Peracetic acid's efficacy in inactivating *E. coli* and total coliforms was comparable to chlorine, and peracetic acid reduced sulfides significantly more than chlorine treatment (Freitas et al., 2021)

Various peroxide compounds are effective as anti-microbial pesticides (Abdelshafy et al., 2024; Banach et al., 2020; Robbins et al., 2005). Hydrogen peroxide and peracetic acid are recognized as viable alternatives to chlorine and alkali products to clean milking machines and dairy equipment and as shell egg sanitizers (Ecolab, 2025; NYSCHAP, 2025a). These National List substances are also allowed to be used to sanitize organic shell eggs (Biosafe, 2017; Negrete, 2014).

Researchers compared different disinfection treatments for poultry houses, investigating the reduction of coliforms, *Staphylococcus* spp., *Pseudomonas* spp., and total aerobes (D. White et al., 2017). One of the treatments was a cleaning compound composed of potassium hydroxide and sodium hypochlorite diluted to 3 oz/gal solution. Other treatments included 4.3% hydrogen peroxide solution diluted to 2 oz/gal and a peracetic acid (5.9%)/hydrogen peroxide (27.3%) mix also diluted to 2 oz/gal. The hydrogen peroxide and peracetic acid/hydrogen peroxide treatments were not significantly different from the potassium hydroxide/sodium hypochlorite treatment in reducing coliform, *Staphylococcus,* and *Pseudomonas* in layer cages, although the hydrogen peroxide treatment alone was significantly less effective in reducing the total aerobic bacterial count after treatment. When used in pullet cages, the potassium hydroxide/sodium hypochlorite treatment was the most effective (D. White et al., 2017).

When compared with chlorination and ozonation, peroxyacetic acid was the most effective treatment to eliminate biofilms related to *Listeria monocytogenes* (Robbins et al., 2005).

Turabekov et al. (2024) found that a hydrogen peroxide-based disinfectant reduced microorganism counts in poultry houses by over 80% after three hours of exposure.

Hydrogen peroxide and peracetic acid are recognized as viable disinfectants and sanitizers for the post-harvest handling of organic fresh fruits and vegetables (Silva, 2009; Suslow, 2000). Producers can use peroxy compounds as an alternative to chlorine to prevent mold and other decay-causing organisms in fruit and vegetables.

Hydrogen peroxide can be used as a teat dip (Belsito, 2012; Karreman, 2004; Leslie et al., 2006). While the National Mastitis Council protocol has conducted few studies on the efficacy of hydrogen peroxide, the anecdotal results are favorable (Belsito, 2012). We searched the NIH DailyMed database on October 12, 2025 and found 13 teat dip products that listed hydrogen peroxide as the active ingredient (U.S. NLM, 2025a).

Peroxy compounds can also be used in honey production (Bojanic Rasovic, 2021). They have the advantages of being fast-acting and decaying into relatively non-toxic by-products. Peracetic acid is also effective at lower temperatures. Peracetic acid is also active in the presence of organic matter. Hydrogen peroxide and peracetic acid have the disadvantage that they can be corrosive to various metals. Peracetic acid is unstable when diluted (Bojanic Rasovic, 2021).

EPA approved sanitizers without chlorine

The EPA has registered various anti-microbial pesticides that are recognized under the "Design for the Environment" (DfE, formerly "Safer Choice") label (EPA, 2025a). Such products are required to meet federal pesticide laws, including efficacy requirements. Products that have citric acid, lactic acid, and ethanol as antimicrobial active ingredients are on the DfE list. A list of DfE certified products is included in *Table 7* (EPA, 2025a). It is unclear if the commercial products in *Table 7* would be allowed for use in organic production.

Table 7: Non-chlorine sanitizers recognized under the EPA's DfE label as of September 16, 2025 (EPA, 2025a).

Company	Product	Active ingredient	EPA Reg. #
Airex Laboratories	Airx CitroRx Botanical Disinfectant Cleaner & Odor Counteractant Tuberculocidal, Fungicidal and Sanitizer	Citric acid	810-35-44089
Clorox Professional Products Company	CloroxPro™ Clorox® EcoClean Disinfecting Cleaner	Lactic acid	67619-45
Clorox Professional Products Company	CloroxPro Clorox EcoClean Disinfecting Wipes	Citric acid	67619-48
GOJO Industries, Inc.	PURELL Professional Surface Disinfectant, Disinfects Food Contact Surfaces - Citrus	Ethanol	84150-3
GOJO Industries, Inc.	PURELL Healthcare Surface Disinfectant, No Bleach, No Harsh Fumes	Ethanol	84150-4
GOJO Industries, Inc.	PURELL Foodservice Surface Sanitizer, No Rinse Required - Fragrance Free	Ethanol	84150-3
GOJO Industries, Inc.	PURELL Food Processing Surface Sanitizer, Registered D2, No Rinse - Citrus	Ethanol	84150-3
Intercon Chemical Company	RTG READY TO GO TB Disinfectant Cleaner	Citric acid	34810-35-48211
Lucas Products Corp.	Lucas-Cide CA	Citric acid	34810-35-3974
Midlab, Inc.	Maxim Citric Acid Disinfectant RTU	Citric acid	34810-35-45745
Radienz Living	ECOS PRO Multi-Surface Disinfectant & Sanitizer, fresh citrus	Citric acid	34810-35-82206
Spartan Chemical Company	Green Solutions Restroom Cleaner	Citric acid	5741-25
Spartan Chemical Company	FP PRO Food Contact Sanitizer	Ethanol; isopropanol	5741-36
Spartan Chemical Company	X-Effect Restroom Cleaner with Citric Acid	Citric acid	5741-25
Summit Brands	Glisten Dishwasher Cleaner	Citric acid	9902-2
Waxie's Enterprises, LLC, an Envoy Solutions Company	WAXIE-Green Disinfecting Wipes	Citric acid	34810-37-14994
Zogics LLC	EcoPro Disinfecting Wipes	Citric acid	34810-37-84918

Evaluation Question #10: Describe any alternative practices that would make the use of this substance unnecessary [7 U.S.C. 6518(m)(6)].

In addition to nonsynthetic and allowed synthetic disinfectants, there are also a number of physical and cultural alternatives to chlorine use (see *Table 8*).

Table 8: Physical and cultural alternatives to chlorine materials

Alternatives	Scope/Use/Sources
Filtration	**Crops:** irrigation water treatment (Nakayama & Bucks, 1991; Raudales et al., 2014); wastewater treatment (EPA, 2012). **Handling:** fruit and vegetables (Meireles et al., 2016).
Heat and steam	**Crops:** farm tools, machinery, and equipment (Olsen & Nolte, 2011; Weicherding, 2006); **Livestock:** barns, facilities, feeders (HFHA, 2024); equipment in contact with raw fluid milk (Farrall, 1929; Sigurdson et al., 2004); shell egg disinfection (Keener, 2017) **Handling:** food contact surfaces (Marriott et al., 2018); fruits and vegetables (Ban et al., 2014; Ban & Kang, 2018).
Pressure	**Handling:** fruits and vegetables (Ali et al., 2018).
Ultrasound	**Crops:** farm tools, machinery, and equipment; seed treatment (Gordon, 1963; Mihaylova et al., 2021). **Livestock:** equipment in contact with raw fluid milk (Botto et al., 2001); shell egg disinfection (Galiş et al., 2013). **Handling:** food contact surfaces; fruits and vegetables (Ali et al., 2018).
Ultraviolet light	**Crops:** irrigation water treatment (Raudales et al., 2014); wastewater disinfection (EPA, 1999, 2012). **Livestock:** barns, facilities, feeders; livestock drinking water; shell egg disinfection (Galiş et al., 2013). **Handling:** food contact surfaces (Marriott et al., 2018); carcass disinfection (Chiozzi et al., 2022); fruits and vegetables (Bermúdez-Aguirre & Barbosa-Cánovas, 2013; Suslow, 2006).

Filtration

The need to chlorinate water can be reduced or eliminated by the physical removal of organisms and particles with a filter, depending on the use and application.

Crops

Water fed into drip irrigation systems can have suspended materials removed by sand or screen filters, or by centrifugal separators (Nakayama & Bucks, 1991). A backwashing self-cleaning drip irrigation system successfully prevented clogging by silt and algae with screen filters with mesh sizes of 124 µm (micrometer/micron) and 178 µm, combined with adequate backwashing at suitable pressures (Zong et al., 2019). As noted above, chlorination may address algal clogging but not siltation (Nakayama & Bucks, 1991). Filtration may be less effective in organic farming systems because organic fertilizers fed into irrigation systems are rarely true solutions, with suspended solids that may be trapped by the filter (Simonne et al., 2008). If suspended fertilizer particles are removed by the filters, the amount of effective fertilization is diminished (Simonne et al., 2008).

Handling

Membrane filtration, microfiltration, nanofiltration, and reverse osmosis may be used to treat produce wash water (Meireles et al., 2016). Filtration can also be used to increase the efficiency of ozone disinfection (Suslow, 2000). The practice is not widely adopted because of the high cost, high maintenance requirements, and limited life span of the equipment (Meireles et al., 2016).

Heat and steam

Heat offers the widest range of efficacy among all disinfection methods and is non-toxic (Addie, 2024). Heat and steam can be used in organic crop, livestock, and handling production for most purposes that chlorine is applied.

Crops

Steam can be used to disinfect farm equipment and tools with fewer corrosive effects on steel than chlorine compounds (Olsen & Nolte, 2011; Weicherding, 2006). Steam and heat can also be an effective physical method to disinfect soil and growth media (van Loenen et al., 2003).

In one study, researchers collected soil samples from two sites, sterilized the soil by autoclaving, and placed samples in containers (van Loenen et al., 2003). The sample containers were separately infected with the soilborne plant pathogens or weeds:

- *Sclerotium cepivora* (white rot)
- *Sclerotinia sclerotiorum* (white mold)
- *Verticillium dahlia* (causal agent for verticillium wilt)
- *Pythium ultimum* (causal agent for damping off and root rot diseases)
- *Globodera rostochiensis* and *Globodera pallida* (potato cyst nematodes)
- *Chenopodium album* seeds (lamb's quarters, a weed)
- *Agropyron repens* rhizomes (quackgrass, a weed)

The soil containers were then treated with steam generated by a heat exchanger for about two minutes. Temperatures ranged from 50 °C to 80 °C (122-176 °F) except for the containers with *A. repens,* which were treated at 50 °C (122 °F) and 60 °C (140 °F). The effect of steam on the pathogens and weeds was mixed. Steam was effective at controlling *P. ultimum,* but not *S. cepivora* or *V. dahlia*. Temperatures above 50 °C eliminated the nematode species. The *C. album* weed seeds and *A. repens* rhizomes also survived the treatment (van Loenen et al., 2003).

Livestock

Hot water or steam will inactivate most pathogens in animal living areas, such as pens and hutches (HFHA, 2024). Wood, metal, and concrete surfaces can be disinfected with steam and power washing (HFHA, 2024). Heat and steam has a wide range of veterinary uses (Addie, 2024). Pathogens that are difficult to kill with chemical disinfectants, such as bacterial spores, mycobacteria, protozoal oocysts, parvoviruses, and prions can be eliminated by the application of steam heat. Surgical instruments can be sterilized by autoclaving at 126 °C (259 °F) at 20 psi for 10 minutes. Prions can be inactivated by a temperature of 130 °C (266 °F) for 30-60 minutes (Addie, 2024).

Milk machines and dairy equipment can be sanitized by applying and retaining hot water at a temperature of 77 °C (170 °F) for five minutes (Jones, 2009; Sigurdson et al., 2004). The bulk milk tank should be completely drained of the hot water after sanitizing to avoid mineral buildup (Sigurdson et al., 2004).

Heat can also be used to prevent honeybee diseases and parasites (USU Beekeeping Extension, 2024). However, incineration of infected hives is regarded as the only effective treatment for preventing the spread of American foulbrood (Mahdi et al., 2022).

Shell eggs can be pasteurized by heating in a warm water bath under controlled conditions that reduce *Salmonella* spp. but do not cook the egg (Keener, 2017). The FDA recognizes the process as effective and eggs that have been pasteurized in-shell are not required to carry safe handling instructions on the carton (FDA, 2022). The methods used to pasteurize eggs is a patented process (Cox et al., 1996).

Handling

Processors have used heat for many years to ensure food safety (Potter & Hotchkiss, 1998). Boiling water under pressure to generate steam at temperatures above the boiling point of water can be an effective sanitizer and disinfectant for many applications (Cenkowski et al., 2007). Steam used to handle and process food can be saturated liquid, saturated vapor, or superheated (Toledo, 1999).

Unsaturated or wet steam is made simply by boiling water to 100 °C (212 °F). The water vapor contains both liquid water and steam. While wet steam (unsaturated water vapor) is commonly used in many food processing and handling facilities and can be effective at removing dirt and preparing surfaces, liquid condensation makes it unreliable as a disinfectant (Marriott et al., 2018; Troller, 1993).

Saturated steam (also called dry steam) is water that is entirely vaporized (Moran et al., 2018; Toledo, 1999). To create this, heat is added to the steam so that all the liquid water particles turn into gaseous steam. This type of steam contains no liquid water particles in the vapor. The heat that is added is "latent," meaning that it does not result in a temperature change. Instead, the heat is used to drive the phase change from liquid to gas. Pressure is often used to assist in the creation of saturated steam.

Once all the water molecules are gaseous, added heat once again can increase the temperature of the system. Superheated steam can be created by continuing to heat dry steam. Often this uses pressure and heat to increase the temperature of dry (saturated) steam (Moran et al., 2018; Toledo, 1999).

Researchers compared the efficacy of saturated steam and superheated steam to inactivate *E. coli*, *S. typhimurium,* and *L. monocytogenes* and control microbial biofilms on polyvinyl chloride and stainless steel (Ban et al., 2014). Food contact surfaces were infected with the pathogens and treated with distilled water, saturated steam, steam superheated to 150 °C (302 °F), and steam superheated to 200 °C (392 °F) for durations between 5 and 30 seconds. Pathogen survival was a function of temperature and duration, with no surviving organisms at 200 °C (392 °F) for 10 seconds or more (Ban et al., 2014).

Some food products can be decontaminated using superheated steam (Cenkowski et al., 2007). While this method is generally used on grains and other non-perishable products, superheated steam can also be used on some fresh fruits and vegetables (Cenkowski et al., 2007). Researchers inoculated cantaloupes with *E. coli*, *Salmonella typhimurium,* and *Listeria monocytogenes* and then treated them with 2% lactic acid and steam superheated to 200 °C (392 °F) for 20 seconds. The treated cantaloupes had no detectable pathogens and retained their sensory qualities (Kwon et al., 2019).

In another experiment, researchers treated inoculated cherry tomatoes and oranges with *E. coli*, *S. typhimurium,* and *L. monocytogenes*, then treated them with saturated steam and superheated steam at various temperatures and durations (Ban & Kang, 2018). Cherry tomatoes treated for 3 seconds and oranges treated for 20 seconds had no surviving pathogens after treatment with steam superheated to 200 °C (392 °F). The treatment resulted in no significant changes to color, texture, vitamin C content, or antioxidant capacity (Ban & Kang, 2018).

Researchers compared short-duration steam treatment with chlorine application for the disinfection of fresh-cut lettuce (Martín-Diana et al., 2007). Lettuce was prepared with 120 ppm chlorine in one treatment and was blanched by steamer jet injection for 10 seconds in the other treatment. The lettuce was stored at 4 °C (39 °F) for 10 days and evaluated. There was no significant difference in the mesophilic bacterial cell counts resulting from the two treatments. Shelf life was also similar. The blanched lettuce showed slight browning, but was still acceptable to the sensory panel (Martín-Diana et al., 2007).

<u>Pressure</u>

High-pressure processing (HPP), also known as high hydrostatic pressure (HHP) processing, is another way to inactivate microorganisms without the use of chlorine materials (Aganovic et al., 2021; Chiozzi et al., 2022). The technique usually involves putting products into packages designed to withstand high pressure and subjecting them to hydrostatic pressure between 100 and 1,000 MPa and temperatures between 0 °C and 120 °C (32 °F - 248 °F) (Chiozzi et al., 2022).

The main commercial application for pressure treatment is to decontaminate meat and meat products (H.-W. Huang et al., 2017). High-pressure processing can reduce *E. coli* and *Salmonella* by 5 logs in ready-to-eat meat and poultry products, but some strains are pressure-resistant (FSIS, 2012). The USDA's FSIS requires their inspectors to verify that meat and poultry processors that use high-pressure processing have a Hazard Analysis and Critical Control Point plan that is effective in achieving the target 5-log reduction (FSIS, 2012).

High-pressure processing is also used as an alternative to pasteurizing fruit and vegetable juices (H.-W. Huang et al., 2017); however, high hydrostatic pressure is not suitable for most raw, unprocessed fruits and vegetables (Aganovic et al., 2021). One potential exception is carrots (*Daucus carota*) because they are firm enough to withstand pressure without physical damage (Aganovic et al., 2021; Knockaert et al., 2011). While a pilot study showed promising results, there is no evidence that the practice is commercially feasible (Vervoort et al., 2012).

Ultrasound

Ultrasound involves the use of sound waves that are above the frequency detectable by the human ear, which is nominally 20 kHz (Lacefield, 2014). The intensity of ultrasound can also vary by the amount of energy used to generate the sound (Ali et al., 2018). Ultrasound waves form gas bubbles in cells caused by the sound frequencies in a process known as "cavitation" (Lacefield, 2014). Depending on frequency, intensity, time, temperature, target organism, and other factors, ultrasound can dislocate, damage, or destroy a broad range of microbial cells, including bacteria, fungi, algae, and viruses through non-chemical modes of action (Nakonechny & Nisnevitch, 2021). Disruption of microbial cell membranes from high intensity ultrasound causes cell solutes to leak and lose osmotic responsiveness that can result in cell death (Bhargava et al., 2021).

Agricultural applications of ultrasound were first explored in the early 1960s (Gordon, 1963). Most agricultural applications involve using low-intensity ultrasound to monitor soil physical properties, plant health, seed quality, pests and diseases, and fruit ripening (Sattar & Laila, 2025). Researchers proposed that high-intensity ultrasound is a potential alternative to pesticides as an antimicrobial treatment (Gordon, 1963). Another application of ultrasound is the disinfection of seed from seed-borne diseases (Mihaylova et al., 2021).

Low-intensity ultrasound has a long history of use in milk production to guide insemination decisions, evaluate pathological conditions of the uterus prior to insemination, diagnose pregnancy, monitor embryo mortality, evaluate fetal malformations, and determine sex for reproduction management (Fricke, 2002; Quintela et al., 2012). Producers can also use ultrasonic methods for veterinary diagnostics and decision-making (Braun et al., 2013). Non-destructive methods—those that do not cause cell damage—are also used for milk and dairy product quality control (Mohammadi et al., 2014). However, high-intensity ultrasound does not appear to be widely adopted as a tool to decontaminate and sanitize milking equipment on farms, even though the practice was shown to be technically feasible in the early 2000s (Botto et al., 2001).

Producers can employ high-intensity ultrasound effectively for food handling decontamination, disinfection, and sanitization for a wide range of applications (Chinchkar et al., 2022; Chiozzi et al., 2022; Singla & Sit, 2021; Welti-Chanes et al., 2017).

Ultraviolet light

Ultraviolet light (UV) treatment is a physical method that can be used to disinfect water (EPA, 2012) and decontaminate food (Chiozzi et al., 2022; Rawson et al., 2011). Light on the electromagnetic spectrum with wavelengths between 200-280 nm (UV-C) has germicidal properties (Choudhary & Bandla, 2012). UV-C absorbed by an organism's DNA inactivates microbes and damages proteins (Chiozzi et al., 2022). DNA photoproducts formed by the waves result in mutation and cell death (Chiozzi et al., 2022).

UV light is recognized as an alternative to chlorine for the treatment of wastewater (EPA, 1999).

FDA regulations allow UV to be used on food and food products for surface microorganism control, to sterilize water used in food production, and to reduce human pathogens and other organisms in juice products [21 CFR 179(b)]. To comply with FDA regulations UV-C must be generated by low-pressure mercury lamps with 90% emissions of a wavelength of 253.7 nm [21 CFR 179(a)]. The FDA does not classify UV-C as "ionizing radiation" at 21 CFR 179.26, thus it is not prohibited under USDA organic regulations at 7 CFR 205.105(f).

UV-C can be used to disinfect:

- water (Scarlett et al., 2016; Shannon et al., 2008)
- fresh fruits and vegetables (Bermúdez-Aguirre & Barbosa-Cánovas, 2013; Chiozzi et al., 2022; R. Huang et al., 2018; Meireles et al., 2016; Suslow, 2006)
- meat and poultry products (Chiozzi et al., 2022)
- nuts (Gyawali et al., 2024)
- milk and dairy products (Chawla et al., 2021; Chiozzi et al., 2022)
- juices (Koutchma et al., 2016; Rawson et al., 2011)

The efficacy of UV-C varies by food type, target organism, radiant energy, and exposure time (Bermúdez-Aguirre & Barbosa-Cánovas, 2013; Chiozzi et al., 2022).

Crops/Livestock Focus Questions

<u>Focus Question #1: Do chlorine concentrations that are within the maximum residual disinfectant limit (MRDL) impart significant sanitizing properties to water?</u>

Does chlorine within the MRDL sanitize drinking water?
All public water systems that comply with the SDWA effectively operate with chlorine concentrations within the MRDL of 4.0 mg/L or 4 ppm and less of total chlorine to ensure safety from both biological and chemical risks (EPA, 2020). Most drinking water systems in the U.S. and other developed countries safely operate within the MRDL (Black & Veatch Corp., 2010). The EPA established the chlorine MRDL to address the complex balance of water disinfection risks and benefits (EPA, 2020). Because of its high toxicity to microorganisms, chlorine sanitizers can inactivate microorganisms at concentrations that are below the MRDL set by EPA when the total chlorine demand is low (Black & Veatch Corp., 2010). Drinking water must be treated at a level effective at reducing water-borne pathogens to meet safe potability standards, while minimizing the risks posed by disinfection byproducts (National Research Council & Safe Drinking Water Committee, 1987).

Chlorine is regarded as the sanitizer of choice because of its high efficacy at low concentrations (Black & Veatch Corp., 2010). A concentration of 0.1 ppm was shown to be sufficient to kill *E. coli* with a contact time of 24 seconds (National Research Council & Safe Drinking Water Committee, 1987). Water that is low in organic matter and contains few target organisms can be safely disinfected with available chlorine levels below 1 ppm (Bertelli et al., 2018; Black & Veatch Corp., 2010). Public water supply systems in Germany and the United Kingdom regularly supply safe, clean drinking water using less than 0.3 mg/L for chlorine and less than 0.2 mg/L for chlorine dioxide (Black & Veatch Corp., 2010). Municipal water supply operators in two French cities reduced free chlorine levels in drinking water from an average of 0.11 and 0.24 mg/L to 0.06 and 0.08 mg/L (Bertelli et al., 2018). The treatment at the lower rate was still effective in controlling microbial colonies and reducing biofilm (Bertelli et al., 2018).

Thus, chlorine concentrations that are within the MRDL unequivocally impart significant sanitizing properties to drinking water.

Can chlorine at levels within the MRDL (4.0 mg/L or 4 ppm and less) act as a sanitizer in water that is used for other purposes?
When water is used for purposes other than drinking—such as irrigation, cleaning equipment, used on food and food contact surfaces, and for any other purposes along the food supply chain—the answer to whether or not chlorine at levels within the MRDL can act as a sanitizer is more complicated (Simpson & Mitch, 2022).

The amount of free chlorine needed to effectively sanitize food and food contact surfaces in various other applications depends on many different factors, including:

- water source (Black & Veatch Corp., 2010; Suslow, 1997)
- pretreatment prior to chlorination (Shannon et al., 2008; Shevah, 2016)
- concentration of available chlorine (Black & Veatch Corp., 2010; Gallandat et al., 2021; National Research Council & Safe Drinking Water Committee, 1980; Suslow, 1997; Troller, 1993)
- form of chlorine (Gallandat et al., 2021; Marriott et al., 2018; National Research Council & Safe Drinking Water Committee, 1980)
- water pH (Gallandat et al., 2021; National Research Council & Safe Drinking Water Committee, 1980; Suslow, 1997; Troller, 1993)
- water temperature (National Research Council & Safe Drinking Water Committee, 1980; Troller, 1993)
- organic matter load (Marriott et al., 2018; Troller, 1993)
- other chemical demand (Black & Veatch Corp., 2010)
- target organisms (Gallandat et al., 2021; National Research Council & Safe Drinking Water Committee, 1987; Suslow, 2004)
- biofilms protecting the target organisms (Marriott et al., 2018)
- contact time with the target organism (Suslow, 1997)

All these factors affect the availability, effectiveness, and demand for chlorine. This in turn affects how much chlorine is needed to sanitize a given surface or product.

<u>Water source</u>
Because of the potential for fecal pollution, surface waters (and ground water sources that are influenced by surface water) are likely to have a greater microbial load than deeper ground water (EPA, 2020; National Research Council & Safe Drinking Water Committee, 1987). Under EPA's ground water rule (40 CFR 141.400 *et seq.*), a public water

supply that uses groundwater (not under the direct influence of surface water) and in which fecal coliform is monitored daily is not required to chlorinate or otherwise treat their water for pathogens unless it tests positive for total coliform. Such systems are chlorinated as needed and are required to be within the available chlorine MRDLs within the SDWA [40 CFR 141.65(a)].

Pretreatment prior to chlorination

Various pretreatments that remove dissolved organic matter can lower the chlorine demand and reduce the quantity of disinfection by-products produced by the disinfection process (Oziegbe et al., 2023; Shannon et al., 2008; Shevah, 2016). One approach is to use reverse osmosis followed by UV light (Shannon et al., 2008). Another is to use biologically based flocculants to bind with the organic matter, pulling it out of suspension and making it easier to remove prior to chlorination (Shevah, 2016). Another approach is to use ozone as a pretreatment prior to chlorination (Verdugo et al., 2020). If effective pretreatment processes are used and the amount of chlorine that is applied stays the same, then relatively more free chlorine is available downstream.

Chlorine concentration and form

The concentration of the chlorine is a major factor in determining its effects (Gallandat et al., 2021; National Research Council & Safe Drinking Water Committee, 1980; Suslow, 1997). Higher concentrations of chlorine are more effective in killing the target organisms in a wide range of settings, with diminishing effects at the highest doses (Gallandat et al., 2021). Hypochlorous acid has an antimicrobial activity that is 80 times more effective than the hypochlorite ion (Marriott et al., 2018). As such, sources that generate hypochlorous acid rather than the hypochlorite ion are more likely to be effective within the MRDLs, all other factors being equal (Marriott et al., 2018).

Water pH and temperature

Water temperature has a significant effect on the inactivation of most target organisms (Black & Veatch Corp., 2010). Chlorine becomes less effective as temperatures decrease (Black & Veatch Corp., 2010). For example, at temperatures above 50 °C (122 °F), Cl_2 solubility decreases (Marriott et al., 2018).

Chlorine's effectiveness as an antimicrobial is also pH dependent (Black & Veatch Corp., 2010; Marriott et al., 2018; Suslow, 1997; Troller, 1993). The optimal range is between 6.5 and 7.5 (Suslow, 1997). As the pH rises (becomes more basic/alkaline), the chlorine species changes from the more effective hypochlorous acid (HOCl) to the less effective form of the hypochlorite ion (ClO^-) (Black & Veatch Corp., 2010).

Organic matter load

Chlorine reacts with leaves, soil, and any other plant or vegetable material when oxygen is present (Suslow, 1997). Chlorine's biocidal activity decreases when available (or free) chlorine reacts with organic matter instead of living organisms that are the intended target (Black & Veatch Corp., 2010; National Research Council & Safe Drinking Water Committee, 1980). Therefore, it is best practice to remove as much organic matter as possible prior to chlorination (National Research Council & Safe Drinking Water Committee, 1980; Suslow, 1997).

Other chemical demand

Chlorine can react with other chemicals in the water, such as iron, which also decreases its disinfection efficiency (Black & Veatch Corp., 2010). As noted in the *Specific Uses of the Substance* section and *Evaluation Question #3*, when chlorine and iron react, the iron precipitates, which can interfere with equipment (Nakayama & Bucks, 1991).

Target organisms and biofilms

Parasites such as *Giardia lamblia, Cyclospora* spp., and *Cryptosporidium parvum* are relatively resistant to chlorine (Bihn & Reiners, 2018; National Research Council & Safe Drinking Water Committee, 1987). *Cyclospora* is of particular concern to the fresh produce industry because it has been responsible for many foodborne illness outbreaks (Bihn & Reiners, 2018). Ozonation, peroxyacetic acid, or high intensity UV light treatment are more effective in controlling *Cyclospora* than chlorine or other halogenated sanitizers (Suslow, 2004). Biofilms can form over various organisms making them impervious to the biocidal effects of chlorine (Marriott et al., 2018).

Contact time

Conditions where chlorine demand is greater may require longer contact times to meet the EPA's regulations (authorized under the Safe Drinking Water Act) at lower doses of chlorine (EPA, 2007). For example, researchers have found that levels of available chlorine as low as 0.2-0.5 ppm are effective against a broad range of pathogens with a contact time of 30 minutes (Oziegbe et al., 2023).

Chlorine applications other than drinking water

The best available technology for the disinfection of drinking water is relatively uniform and well understood, and postharvest handling facilities are highly variable based on their location and the specific foods they process

(Simpson & Mitch, 2022). The MRDLs are clearly sufficient to provide clean and potable *water*, however, it is less certain whether water with available chlorine at these levels can effectively disinfect *food* or food contact surfaces (Simpson & Mitch, 2022). Some food safety regulations require pathogens of concern to be reduced by 99.999% (10^5), which is referred to as a five-log reduction (FDA, 2004; US FSIS, 2021). For applications other than potable drinking water, such as process wash water used in direct contact with vegetables, fruits, meat, and poultry, the question of effective chlorine level is more difficult to answer (Simpson & Mitch, 2022; Suslow, 1997; Tudela, López-Gálvez, Allende, & Gil, 2019; Weng et al., 2016; Wirtanen & Salo, 2003).

Disinfection of drinking water differs from sanitization of food using process wash water in several significant ways (Simpson & Mitch, 2022). One is that the contact time for chlorine in drinking water exceeds 5 minutes and can be hours long (Black & Veatch Corp., 2010; Simpson & Mitch, 2022). Commercial operations that wash fruits and vegetables employ a contact time of 5 minutes or less (Simpson & Mitch, 2022; Suslow, 1997; Tudela, López-Gálvez, Allende, & Gil, 2019).

Another factor is that putting solid food into wash water immediately increases the dissolved organic matter content, and with it the demand for available chlorine (Simpson & Mitch, 2022). Levels of available chlorine used to wash leafy greens and root vegetables will fluctuate based on the chlorine demand (Weng et al., 2016). Root crops, such as potatoes, will have a considerable amount of soil on their surfaces and will require higher concentrations of chlorine to be effective for disinfection, with levels as high as 600 ppm (Suslow, 1997). Rapid changes in disinfectant demand make it difficult to determine actual levels of available chlorine in the system at any given time, and whether the levels are sufficient to be effective at sanitizing the food (Tudela, López-Gálvez, Allende, & Gil, 2019; Tudela, López-Gálvez, Allende, Hernández, et al., 2019). Monitoring for compliance with USDA organic regulations is complicated because chlorine levels can vary widely depending on the point in the process where available chlorine is measured and what sensors are used for monitoring (Suslow, 2006).

An effective sanitation program requires a systems approach (Marriott et al., 2018). It is feasible in some cases to disinfect food using chlorine doses that are within the MRDL for drinking water if a systems approach is used, at least for some foods and applications (Marriott et al., 2018; Troller, 1993).

Adams et al. (1989) conducted an experiment using tap water treated by the water supplier with measured available free chlorine of <0.2 mg/L with no chlorine added by the researchers. Common tap water reduced microorganisms on lettuce an average of 92.4%. Tap water alone was able to wash away most microorganisms on the surface leaves, but some remained on the inner leaves. In comparison, researchers added 100 mg/L of available free chlorine at neutral pH, which reduced the microbial count by 97.8%. The reduction was pH dependent. Treatment with 100 mg/L free chlorine with the pH reduced to 4.5-5.0 by acetic, citric, lactic, propionic, or sulfuric acid resulted in a consistent five-log reduction with five minutes contact time (Adams et al., 1989).

Migliaccio et al (2009) found that continuous flow of 1 ppm available chlorine is effective at controlling most target microorganisms in irrigation systems. The maximum amount of available chlorine for EPA registered chlorine products that are labeled for use to prevent the clogging of irrigation lines is 5 ppm for continuous flow and 20 ppm for a shock treatment (EnviroTech Chemical Services, 2017). Researchers found that available chlorine levels of about 2 ppm are effective (Migliaccio et al., 2009).

In some cases, chlorine effectiveness is diminished beyond a certain concentration. Bartenfeld et al. (2014) found that poultry chiller water chlorinated to a level of 500 ppm did not significantly reduce the number of viable *Salmonella* that were recovered from a whole carcass rinse. The results were comparable to disinfection rates in previous experiments at the chlorine levels of 50 ppm currently allowed. *Salmonella* was present in 29% of the untreated carcasses, 38% of the carcasses treated with water, and 36% of the carcasses treated with 500 ppm chlorine (Bartenfeld et al., 2014).

Focus Question #2: Do the higher initial application rates indicated in the 2024 technical report increase the likelihood of formation of carcinogenic trihalomethanes when chlorine materials interact with organic matter? Please expand on this and add any new findings.

Yes. Trihalomethanes and other disinfection by-products of water chlorination are formed by the reaction of reactive chlorine species with organic matter (Barrett et al., 2000; Bond et al., 2012; Mazhar et al., 2020; National Research Council & Safe Drinking Water Committee, 1987). Trihalomethanes exist in the environment at low levels as natural by-products from various sources (Hoekstra et al., 1998; Huber et al., 2009). These are detected at the nanograms per liter (ng/L) or parts per trillion (ppt) scale (Hoekstra et al., 1998). These levels are significantly lower than anthropogenic sources that use reactive chlorine species at operational levels used for sanitizing and disinfection, where levels are measurable at mg/L, parts per billion (ppb), or parts per million (ppm) scale (National Research Council & Safe Drinking Water Committee, 1987). This suggests that anthropogenic sources are more common.

Researchers have found a positive correlation between increased chlorine doses and trihalomethane formation under both experimental and field conditions (Abdullah et al., 2009; Asadollahi et al., 2025; G. Hua & Yeats, 2010; A.-T. Huang & Batterman, 2009; Liang et al., 2024). The trihalomethane formation potential is a function that is strongly correlated with the concentration of available chlorine and natural organic matter precursors, primarily in the form of humic acids (Bond et al., 2012; Sathasivan et al., 2020). Increasing the levels of available chlorine and natural organic matter in an untreated water source will predictably increase the levels of trihalomethanes and other disinfection by-products in the treated water, all other factors being equal (Sathasivan et al., 2020). The formation of disinfection by-products is complicated and involves secondary reactions that are difficult to predict (Clark, 1998; Clark et al., 2001; Gang et al., 2002). However, removing all other factors, the correlation between disinfection by-products formation and chlorine dosage can be expressed as a simple mechanistic relationship where all non-residual chlorine forms disinfection by-products (see *Equation 9*) (Chang et al., 2006; Ike et al., 2020).

$$DBP = S(Cl_0 - Cl_r)^n = S\Delta Cl^n \qquad \text{Equation 9}$$

Where DBP = Disinfection by-products formed, Cl_0 is the initial chlorine dosage, Cl_r is the residual chlorine estimated based on mechanistic considerations, and S and n are statistically estimated.

While chlorine is introduced as a water treatment in many different forms, hypochlorous acid is the major reactive form in most systems (Bond et al., 2012). Researchers studying natural water systems found that approximately 5-10% of hypochlorous acid in the system becomes incorporated into trihalomethanes, but many factors play a role, making predictability difficult. Factors other than concentration—such as pH, temperature, and the level of non-organic chlorine demand—also influence the generation of trihalomethanes and other disinfection by-products of toxicological concern (Bond et al., 2012).

The EPA acknowledges that agricultural applications of chlorine materials as pesticides in crop production may generate trihalomethanes (EPA, 1991). Researchers continue to investigate the sources and causes of trihalomethanes and other carcinogens created by reactive chlorine species released by humans in the environment, mainly from drinking water treatment (Mazhar et al., 2020; Scarlat et al., 2025). Trihalomethanes levels in treated water are influenced by water's physicochemical properties, including temperature, pH, and total organic carbon, and environmental factors related to geography and climate (Scarlat et al., 2025).

Asadollahi et al. (2025) exposed soil samples to varying levels of chlorine disinfectant and dissolved organic carbon at different temperatures and durations. They concluded that the formation of disinfection by-products, including trihalomethanes and haloacetic acids, increased with higher doses of chlorine and longer reaction times. They also found that the ratio of available chlorine to dissolved organic carbon is a key factor, with trihalomethanes relatively stable at ratios at 0.5 to 3 Cl_2/dissolved organic carbon but having a greater than 8-fold increase in trihalomethanes when the Cl_2/dissolved organic carbon ratio was greater than 3. Longer exposure times also resulted in higher trihalomethane concentrations (Asadollahi et al., 2025).

As a general rule, higher levels of available chlorine will result in greater generation of trihalomethanes (Gómez-López et al., 2013). Chlorine levels can be controlled under laboratory conditions, but managing chlorine levels in wash water used by large scale produce handling operations is more difficult (Tudela, López-Gálvez, Allende, & Gil, 2019).

Shen et al. (2016) simulated leafy green handling conditions to estimate disinfection by-products generation. They treated wash water used to clean leafy greens with sodium hypochlorite and citric acid, with free chlorine concentrations between 0.4 and 84.2 mg/L. The added chlorine resulted in significant concentrations of trihalomethanes and haloacetic acids , including monobromoacetic acid, tribromoacetic acid, trichloroacetic acid, and chlorodibromoacetic acid. The levels were correlated with both chlorine and organic matter levels. They found that improved filtration of organic matter reduced the generation of trihalomethane and haloacetic acid (Shen et al., 2016).

Researchers treated lettuce (*Lactuca sativa*), red cabbage (*Brassica oleracea* var *capitata f. rubra*), arugula or rocket (*Eruca sativa*), and onions (*Allium cepa*) with sodium hypochlorite at free chlorine levels of approximately 0, 10, 20, and 30 ppm (Tudela, López-Gálvez, Allende, Hernández, et al., 2019). The researchers monitored trihalomethanes, haloacetic acids, and chlorates created as disinfection by-products of the different treatment levels and microbial load in the water. Disinfection by-products were positively correlated with levels of available chlorine, indicating that higher initial application rates will increase the likelihood of the formation of trihalomethanes (Tudela, López-Gálvez, Allende, Hernández, et al., 2019).

Focus Question #3a: How exactly are the various chlorine materials used in sanitizing irrigation lines, animal drinking water, and milk lines, etc. to meet OFPA [NOP] regulations?

Uses of various chlorine materials are explained above in *Specific Uses of the Substance* and summarized in *Table 2*. We surveyed members of the Accredited Certifiers Association (ACA) Materials Working Group on August 14, 2025. We received three responses within the 12 business day period that the survey was conducted. The ACA Materials Working Group was selected because of their professional experience with input products. The responses were generally consistent with NOP 5026 *The Use of Chlorine Materials in Organic Production and Handling* (NOP, 2024b).

Only one of the certifiers that responded had approved the use of chlorine products in irrigation systems. The most common chlorine product used for irrigation systems was calcium hypochlorite. The certifier did not have specific information on monitoring tools or techniques, but they stated that they verified the monitoring and testing program that they approved in operations' Organic System Plans (OSPs).

All three certifier respondents approved chlorine products for use in livestock production systems. The most common use is in livestock facility sanitation. Sodium hypochlorite is by far the most common chlorine product used by processors. Chlorine dioxide is used to treat livestock drinking water and sanitize water lines. Equipment used to inject chlorine dioxide into water lines will typically have a meter that records the dose, and that is what is used to verify compliance. Processors use test strips for other applications to ensure that chlorine residues will not contact organic products.

All three certifier respondents approved chlorine products for post-harvest handling. They all approved sodium hypochlorite, acidified sodium chlorite, calcium hypochlorite, chlorine dioxide, and hypochlorous acid generated from electrolyzed water. Again, sodium hypochlorite was the most common material used for post-harvest handling, with calcium hypochlorite and chlorine dioxide also common, according to one certifier.

Focus Question #3b: Are they used at any point at concentrations above the 4 ppm limit?

Yes, at least for some uses. See the permitted rates of use in *Table 2.* Organic producers and handlers may apply chlorine at rates above the 4-ppm limit for the following scopes and uses shown below.

Crops

- wastewater treatment
- sanitizing tools, machinery, and equipment
- disinfecting seeds for sprouting

It was not clear from the certifier responses whether chlorine is ever approved for use in drip irrigation systems for a shock treatment, but routine use appears to be within the 4-ppm range even though the maximum label rate is up to 5 ppm. It was also not clear from certifier responses whether any organic producers are using chlorine as a pre-plant treatment for seeds other than those for sprouting.

Livestock

- disinfecting barns, facilities, and feeders
- sanitizing equipment in contact with raw fluid milk
- washing shell eggs

Handling

- sanitizing food contact surfaces, equipment and facilities
- disinfecting fruit and vegetable cooling and wash water
- disinfecting poultry chiller water
- disinfecting carcasses

The responses from certifiers indicated that where NOP 5026 *The Use of Chlorine Materials in Organic Production and Handling* states that the producer or handler can use the labelled rate, and the labelled rate is higher than the 4-ppm limit, they approve Organic System Plans with an appropriate intervening event, where needed (NOP, 2024b). These procedures are verified during inspections.

We received an additional comment from one of the respondents about the need for chlorine to protect food safety. The respondent said that *"[r]esponsible and compliant use of chlorine is a key tool for organic producers to ensure food safety."* They went on to say that *"clean irrigation systems and water can support healthy plants which can result in less reliance on other inputs . . . increased yields . . . [and] higher quality crops . . ."*

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All individuals comply with Federal Acquisition Regulations (FAR) Subpart 3.11—Preventing Personal Conflicts of Interest for Contractor Employees Performing Acquisition Functions.

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Appendix A

Table 9: Glossary of terms

Term	Definition
Available chlorine	The mass of chlorine in solution that has the same oxidizing power as chlorine gas (Cl_2). *See "Free chlorine."*
Chlorine demand	The difference between initial chlorine and residual chlorine.
Disinfectant	1. A chemical agent that eliminates undesirable organisms from inanimate objects. 2. A substance, or mixture of substances that destroys or irreversibly inactivates bacteria, fungi and viruses, but not necessarily bacterial spores, in the inanimate environment (40 CFR 158.2203).
Disinfectant byproducts	Chemical pollutants produced by the disinfection process.
Disinfection	A process that inactivates pathogenic organisms by chemical or other agents.
DOC	Dissolved organic carbon.
Free chlorine	Chlorine in water available for disinfection.
Initial chlorine	The dose of chlorine added to the disinfection process.
Log reduction	A decrease in population of a target organism or set of target organisms following a treatment expressed as a base-10 logarithm (Log10). For example, a 90% decrease or 10% survival is a 1 log reduction, a 99% decrease or 1% survival is a 2-log reduction, and a 99.9% decrease or 0.1% survival is a 3-log reduction.
Maximum Contaminant Level	The highest level of a contaminant that is allowed in drinking water.
Maximum residual disinfectant level	The maximum level of a disinfectant added for water treatment that may not be exceeded without an unacceptable possibility of adverse health effects. MRDLs are enforceable standards under the Safe Drinking Water Act (SDWA) analogous to MCLs.
NOM	Natural organic matter.
Reactive chlorine species	Chlorine-containing compounds capable of chlorinating and oxidizing other molecules, including hypochlorous acid, chlorite, and chlorine gas.
Residual chlorine	The amount of unreacted available chlorine in water after a specified contact time or when the disinfection process is complete in the case of drinking water or effluent.
Sanitize	To treat a surface to reduce microorganisms of public health concern.
Sanitizer	1. A substance or product used to reduce or eliminate pathogenic organisms on surfaces. 2. A substance, or mixture of substances, that reduces the bacteria population in the inanimate environment by significant numbers but does not destroy or eliminate all bacteria (40 CFR 158.2203).
Sanitizing rinse	Sanitizers that meet Public Health Ordinances on food contact surfaces (40 CFR 158.2203).
Total chlorine	The mass of chlorine that is both available and combined with reaction products.
Total trihalomethanes	The sum of the concentration in milligrams per liter of the trihalomethane compounds [trichloromethane (chloroform), dibromochloromethane, bromodichloromethane, and tribromomethane (bromoform)], rounded to two significant figures.
Trihalomethanes	A family of organic compounds that are derivatives of methane where three of the four hydrogen atoms in methane are each substituted by a halogen atom in the molecular structure.