

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

<https://www.ams.usda.gov/rules-regulations/organic/petitioned-substances>

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).

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

Guidelines for submitting a petition are available in the NOP Handbook as NOP 3011, National List Petition Guidelines.

Petitions are posted for the public on the NOP website for Petitioned Substances.

☒ **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 are available to the public on the NOP website for Petitioned Substances.

Contractor names and dates completed are available in the report.

Potassium Hypochlorite

Crops

Identification of Petitioned Substance

Chemical Names:	14	
Cl-H-O · K; ClHO.K; hypochlorous acid; KOCl;	15	CAS Numbers:
potassium chloride oxide; potassium	16	7778-66-7
oxychloride; potassium salt	17	
	18	Other Codes:
Other Names:	19	CID: 23665762
bleach	20	EINECS/EC: 231-909-2
	21	EPA PC code: 129053
Trade Names:	22	EPA SRS Identifier: 153940
AG KLOR ; Agri-Klor; Enviro Klor Potassium	23	UNII: G27K3AQ7DW
Hypochlorite Solution ; Hasa Aura Klor; K-	24	
Klor; Potassium Hypochlorite		

Summary of Petitioned Use

This limited scope technical report provides information to the National Organic Standards Board (NOSB) to support the sunset review of potassium hypochlorite, listed at 7 CFR 205.601(a)(2)(iv). This report focuses on the uses of potassium hypochlorite (a synthetic substance) in organic crop production as an irrigation water treatment. Potassium hypochlorite is used as a form of chlorine. The last full-scope review on chlorine materials was in 2011, prior to the inclusion of potassium hypochlorite in the organic regulations for this purpose (NOP, 2011).

In 2019, the NOSB recommended listing potassium hypochlorite (KOCl) “for the treatment of irrigation water not to exceed the maximum residual disinfectant limit under the Safe Drinking Water Act” (NOSB, 2019). The NOP added potassium hypochlorite to the National List of Allowed and Prohibited Substances (hereafter referred to as “the National List”) as an allowed chlorine material [§ 205.601(a)(2)] in 2022 ([87 FR 16371](#), March 23, 2022). Its annotation specifies that residual chlorine levels in the water in direct crop contact (when used pre-harvest) or as water from cleaning irrigation systems applied to the soil should not exceed the maximum residual disinfectant limit under the Safe Drinking Water Act [4 mg/L (4 ppm)] expressed as chlorine, and 0.8 mg/L (0.8 ppm) expressed as chlorine dioxide.¹

Characterization of Petitioned Substance

Terminology

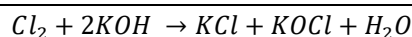
- Free chlorine refers to the sum of molecular chlorine (Cl₂), hypochlorous acid (HOCl) and hypochlorite ions (OCl⁻).
- Combined chlorine is the sum of all the chloramines (NH₂Cl + NHCl₂ + NCl₃).
- Total chlorine (Gray, 2014) or total residual chlorine (Cooke & Schreer, 2001) is the sum of the free and combined residuals.
- The chlorine demand is defined as the difference between the amount of chlorine added to the water and the amount of total residual chlorine that remains at the end of a specified period (Mattice & Zittel, 1976).

¹ Some concentration of disinfectant must remain in the system to be effective over time, in order to provide continuous protection against harmful organisms. In the case of chlorine, this is known as “residual chlorine” (Leidholdt, 2000).

Properties of the Substance

Potassium hypochlorite (KOCl) is a chlorine-based solution sometimes referred to as the potassium salt of hypochlorous acid. It was first produced in 1796 in Javel, France, by dissolving chlorine in caustic potash (Aftalion, 1991).

Potassium hypochlorite is a powerful oxidizing agent produced by the reaction of chlorine with a solution of potassium hydroxide (see [Equation 1](#)):



Equation 1

Potassium hypochlorite is a colorless, pungent compound with an irritating odor. It is made up of potassium cations and hypochlorite anions. It is often diluted in water solution and used at various concentrations.

Hypochlorites are unstable and can lose their disinfecting strength within a few days (Gray, 2014). Hypochlorites decay due to exposure to sunlight, higher temperature, storage at high pH solutions, and contact with certain metals such as copper or nickel. Hypochlorite solutions are very alkaline (pH 11-12), ensuring that the chlorine is stored in the hypochlorite ion (OCl⁻) form. Although corrosive, these solutions are relatively safe to handle (Gray, 2014).

[Equation 2 \(below\)](#) shows the calculation needed to achieve the required concentration of chlorine for use in irrigation water pipe sanitation per the manufacturer of one of the registered products (Enviro Tech Chemical Services, 2014):

$$I = (0.0066) \times (\text{ppm desired}) \times (\text{system rate in gallons per minute}) \\ \div (\text{potassium hypochlorite solution strength})$$

Equation 2

Chemical reactions of chlorine with water

Hypochlorous acid (HOCl) is formed when any form of chlorine is added to water (Leidholdt, 2000). Hypochlorous acid is a very weak acid but a strong disinfectant. Depending on the pH of the added water, hypochlorous acid can dissociate, forming hydrogen ions (H⁺) and hypochlorite ions (OCl⁻).

Hypochlorous acid is produced naturally as well. For example, by (Barnum & Coates, 2022):

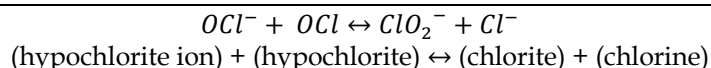
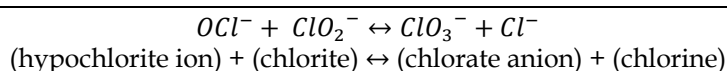
- intracellular haloperoxidases for chlorinating organic molecules
- extracellular haloperoxidases for the decomposition of plant matter
- mammalian immune cells for killing bacteria
- microbial reduction in perchlorate and chlorate
- oxidative chemistry and photochemistry in the environment

Hypochlorous acid and hypochlorite ions are often referred to as “free available chlorine,” indicating that they have not yet reacted with contaminants and can react with other compounds (Leidholdt, 2000). The ratio of HOCl molecules to OCl⁻ ions is important because HOCl is 80 (Gray, 2014) to 100 times (Leidholdt, 2000) more effective as a disinfectant than OCl⁻. The ratio of HOCl to OCl⁻ depends mainly on the pH of the water (Leidholdt, 2000):

- At a pH less than 5.0, approximately 100% of the chlorine is in HOCl form (Leidholdt, 2000).
- At a pH of 7.5, 50% of the chlorine is in the HOCl form (Gray, 2014).
- At a pH greater than 9.0 the hydrogen ions bond with hydroxyl (OH⁻) ions to form water. Therefore 100% of chlorine is present as OCl⁻ (Deborde & von Gunten, 2008; Gray, 2014; Leidholdt, 2000).

To a lesser degree, temperature also affects residual chlorine (Leidholdt, 2000). The colder the water, the longer chlorine will remain in the water. Increasing water temperature causes chlorine to dissipate from the water as a chlorine gas more quickly (Leidholdt, 2000).

Decay of hypochlorite follows second order kinetics with chlorite (ClO_2^-) and chlorate (ClO_3^-) ions being formed according to the following equations (Gray, 2014):²

*Equation 3**Equation 4*

Evaluation Questions for Substances to be used in Organic Crop Production

Classification of the Substance

Evaluation Question #3: Describe any known chemical interactions between the petitioned substance and other substances used in organic crop or livestock production or handling. [7 U.S.C. 6518(m)(1)]. While the initial application rate can be much higher, the maximum residual disinfectant level under the Safe Drinking Water Act for chlorine materials is 4 mg chlorine/L water (NOP, 2024). At the maximum residual disinfectant level, potassium hypochlorite remaining in water that is discharged to fields or the environment is unlikely to have any detrimental interactions with other substances used in organic crop or livestock production or handling. At higher concentrations, potassium hypochlorite may react explosively with finely divided carbon. Potassium hypochlorite solution produces highly toxic chlorine gas fumes upon heating or contact with acids (Sax & Lewis, 2012). It may form highly explosive NCl_3 on contact with urea.

Chemical reaction of chlorine with ammonia

Most natural water contains some amount of inorganic nitrogen in the form of ammonia (NH_3) emitted from decaying organic vegetation. In addition, some water treatment plants add ammonia to the water before chlorination is performed, a process called chlorine–ammonia disinfection (Leidholdt, 2000) or chloramination.

As stated previously, when chlorine (including hypochlorite and other forms) is added to water the chlorine reacts with the water to form hypochlorous acid (Leidholdt, 2000). When the water contains ammonia, the hypochlorous acid then combines with ammonia to form chloramines (nitrogen and chlorine compounds) (Leidholdt, 2000).

There are three types of chloramines that can be formed when chlorine reacts with ammonia (Leidholdt, 2000):

- monochloramine (NH_2Cl)
- dichloramine (NHCl_2)
- trichloramine (NCl_3)

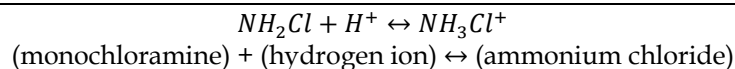
Monochloramine and dichloramine are effective disinfecting agents and are commonly referred to as “combined available chlorine.” Dichloramine is twice as strong a disinfecting agent as monochloramine (Leidholdt, 2000).

² Gray (2014) specifically described the decay of calcium hypochlorite, not potassium hypochlorite; however, other hypochlorite compounds should behave similarly.

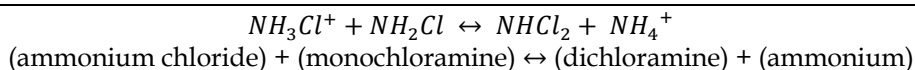
Second order kinetics refers to the rate at which the reactants form chemical products. A second order reaction occurs at an exponential rate (squared).

For complex reasons, the charges shown in Equations 2 and 3 do not balance. This has to do with equilibriums/concentrations of aqueous reactants and products in a reaction with second order kinetics.

In the presence of ammonia, chloramines continue to be formed until a molar ratio chlorine to ammonia ($\text{Cl}_2:\text{NH}_4$) of 1, or a weight ratio of approximately 5.1, with monochloramines produced when the pH is between 7 and 8 (Gray, 2014). At higher ratios and when the pH is below 7, dichloramines and traces of trichloramines are produced in a two-step process (see [Equation 5](#) and [Equation 6, below](#)) (Gray, 2014).



Equation 5



Equation 6

When higher doses of chlorine are added, the chloramines break down, destroying the ammonia and consuming the chlorine (Leidholdt, 2000). This happens when the $\text{Cl}_2:\text{NH}_4$ weight ratio increases from 5.1 to 7.6, as the total chlorine residual declines rapidly and the excess chlorine oxidizes some of the chloramines present producing N_2 and some nitrates (Gray, 2014). The pH value 7.6 is called the “breakpoint,” above which all the residual will be free chlorine (Gray, 2014). The precise $\text{Cl}_2:\text{NH}_4$ weight ratios for the maximum residual and breakpoint depends on the amount of dissolved organic materials and reduced substances present (Gray, 2014; Kirmeyer, 2004).

Many utilities use chloramination for secondary disinfection (Norman et al., 1980). Chloramines are more persistent in water than free chlorine is (Norton & LeChevallier, 1997). In addition, chloramines are less reactive than free chlorine and have been demonstrated to produce lower concentrations of disinfection by-products, such as trihalomethanes and haloacetic acids (Norman et al., 1980).

Inorganic chloramines are degraded by ammonia-oxidizing prokaryotes (archaea and bacteria) and nitrate oxidizing bacteria (Rayson et al., 2010). While inorganic chloramines decay with time, organic chloramines both decay and continue to form, leading to a higher proportion of organic chloramines compared to inorganic chloramines in the total chlorine (Lee & Westerhoff, 2009). Organic chloramines can form from the reaction of dissolved organic carbon or dissolved organic nitrogen with inorganic chloramines or free chlorine (How et al., 2017). Organic chloramines are less effective disinfectants than inorganic chloramines (Donnermair & Blatchley, 2003). The drop in effective chlorine disinfectant residuals creates a favorable environment for nitrifying microorganisms to metabolize ammonia and proliferate, accelerating the nitrification process, which further depletes disinfectant residuals and causes biological and chemical deterioration of water quality (Lee & Westerhoff, 2009).

We were not able to find any research investigating the presence of nitrogen-oxidizing archaea in irrigation water. However, the presence of these organisms in irrigation water is very likely given that nitrifying bacteria are present in municipal drinking water systems. Goraj et al. (2021) studied the effect of pipe construction material (unplasticized polyvinyl chloride, polyethylene high-density or cast iron pipes) on biofilm microbial communities found in drinking water supply system. The results showed that the pipe construction material strongly influences the microbiome composition. For example, unplasticized polyvinyl chloride and polyethylene high-density pipes were dominated with *Proteobacteria* while the cast iron pipe community was mostly composed of *Nitrospirae*. These results indicate that plastic pipes (also often used in irrigation systems) create a more convenient environment for the potentially pathogenic taxa than the cast iron.

Three mechanisms were identified for the decomposition of chloramine species, involving the combination of two chloramine species to form hydrazine, dichlorohydrazine and tetrachlorohydrazine intermediates (Rayson et al., 2010). These species undergo further chlorination and decomposition reactions to form the end products; HCl and N_2 (Rayson et al., 2010).

Other chemical reactions

In addition to the reaction with ammonia to produce chloramines (Leidholdt, 2000), potassium hypochlorite can also react in the following ways (CAMEO Chemicals, 2024; Sax & Lewis, 2012), although these scenarios are unlikely to occur in crop production settings:

- reaction with oil and hydrocarbons
- reaction with nitromethane, methanol, ethanol, and other alcohols; reactions with alcohols may lead to explosions
- reaction (potentially causing ignition and/or explosion) with organic sulfur compounds and with sulfides
- decomposition, evolving oxygen, a change that can be catalyzed by rust on metal containers
- formation of highly explosive NCl_3 on contact with urea or ammonia; evolves highly toxic gaseous chlorine when heated or on contact with acids
- violent reaction with damp sulfur, ejecting molten sulfur

Chlorine reacts in solutions of organic compounds by three basic mechanisms (Morris, 1975):

- addition, during which chlorine atoms are added to a compound
- oxidation
- substitution, during which chlorine atoms are substituted for another atom that is present in the organic reactant

All three of these reactions involve hypochlorous acid as an electrophile.

Evaluation Question #4(A): Discuss the toxicity and mode of action of the substance.

The antimicrobial mode of action of chlorine stems from both oxidation and chlorination (Deborde & von Gunten, 2008). Mixing potassium hypochlorite with water generates highly reactive hypochlorous acid (HOCl), the active ingredient in hypochlorites. Hypochlorous acid forms superoxide radicals that cause oxidative injury and cell death (Juan et al., 2021).³ As pH increases, the proportion of HOCl can partially dissociate into hypochlorite ion (OCl^-) at physiological (neutral) pH levels (Andrés et al., 2022). Hypochlorous acid and its conjugate base, OCl^- , are potent oxidizing agents under physiological conditions (Boecker et al., 2023).

Hypochlorous acid, which predominates at solution pH below 7.5, is 20 to 30 times as effective a sanitizer as the hypochlorite ion (favored by pH above 7.5) (Fisher et al., 2008). The strong oxidizing power of the neutral HOCl species enables it to penetrate pathogen cell walls and membranes (Snell et al., 2022) and remove electrons from those membranes (Raudales et al., 2014). HOCl contributes to the unfolding of proteins through oxidation and the aggregation of essential proteins in bacteria (Winter et al., 2008). This protein unfolding is similar to what happens under heat stress, causing the denatured proteins to clump together into an irreversible mass, therefore impairing their natural functioning (Winter et al., 2008).

Researchers found potassium hypochlorite application to be an effective method of controlling pathogens in hydroponic production systems. For example, Rodriguez et al. (2018) injected electrolytically-derived potassium hypochlorite disinfectant solution into a recirculating nutrient solution to determine its effect on the dispersal of *Fusarium oxysporum* and *Rhizoctonia solani* in hydroponic tomatoes. The potassium hypochlorite solution, applied once a week for 60 minutes at a free chlorine concentration of 0.5 mg L^{-1} , inhibited the dispersal of *F. oxysporum* and *R. solani* during the entire test period of 16 weeks (Rodriguez et al., 2018). A similar inhibitive effect by potassium hypochlorite was observed on the dispersal of Pepino mosaic virus in a greenhouse tomato crop grown using a recirculating irrigation system (Bandte et al., 2016).

The degradation of free chlorine (also termed chlorine demand) requires that growers apply higher amounts of chlorine than what is required at the outlet (Fisher et al., 2008). For example, a specific initial dose of free chlorine (e.g., 5 parts per million) is provided at the well head to ensure adequate residual

³ Mammals naturally produce hypochlorous acid as part of a host defense system, killing invading microorganisms (Winter et al., 2008). Mammalian host defense systems release reactive oxygen and chlorine species that cause damage to the DNA of invading bacteria (Andrés et al., 2022; Juan et al., 2021). Some researchers think this (producing superoxide radicals) is the main defense mechanism mammals use to kill bacteria within tissues (Andrés et al., 2022; Juan et al., 2021).

(typically 0.5 to 2 ppm) at the outlet (Fisher et al., 2008). Research data from the University of Guelph showed that maintaining a rate of 2.4 mg L⁻¹ for five minutes killed all fungi and oomycetes in the irrigation water and controlled most common plant pathogens in container-grown plants (Cayanan et al., 2009).

However, other studies show higher requirements and/or longer exposure time for certain pathogens and certain pathogen forms. A review paper by Raudales et al. (2014) compiled information on the chlorine (mostly using sodium hypochlorite) doses and exposure times required to control different pathogens in their different forms (life stages) and found several pathogens that required higher doses and/or durations. For example, only 47% control rate of *Plasmodiophora brassica* [the pathogenic agent for club root in broccoli (*Brassica oleracea*)] was achieved by treatment of infested irrigation water with 20 mg L⁻¹ for 10 min. under field conditions (Datnoff et al., 1987). The incidence was reduced significantly with 200 mg Cl L⁻¹ compared with the inoculated control, but this treatment also significantly reduced plant height, fresh weight and stand count. A review paper showed that elevated doses of chlorine (20-40 mg/L) are needed for acceptable decrease of viruses in water and wastewater (Gheraout, 2017).

A recent meta-analysis study evaluated the effect of calcium and sodium hypochlorites on fungal pathogens using 109 studies published from 1972 to 2019 (Copes & Ojiambo, 2021). The meta-analysis study concluded that the hypochlorite treatment was most effective in the following descending order: *Fusarium* (most effective) > *Thielaviopsis* > *Botrytis* > *Rhizoctonia* > *Verticillium* (least effective). High variabilities were also observed in the responses of *Fusarium* and *Verticillium*, indicating a wide range of effectiveness depending on the conditions.

Evaluation Question #4(B): Discuss the toxicity and mode of action of its breakdown products or any contaminants.

The hypochlorite breakdown products are chloride, chlorate, and oxygen, with more details presented in [Properties of the Substance](#). Potassium hypochlorite results in potassium chloride as a by-product (Environmental Compliance Resources, LLC, 2013). The mode of action of the breakdown products is presented in *Evaluation Question #4(A)* [above](#).

Chlorine has a rapid decomposition rate, initially as hypochlorite, while in the presence of ammonia it decomposes into chloramines (Batley et al., 2021). Reckhow et al. (1990) measured combined residual chlorine in a small stream just below a municipal wastewater outfall and found that the loss of combined residual chlorine is due primarily to volatilization, with a volatilization half-life of ~7 minutes.

Evaluation Question #4(C): Discuss the persistence of the substance's breakdown products or any contaminants and areas of their concentration in the environment [7 U.S.C. 6518(m)(2)].

Chlorine is converted between different chemical forms by natural processes in a global biogeochemical cycle. Chlorine is released from and returned to rock, added and removed from organic molecules, volatilized and degraded by sunlight, and oxidized and reduced both biotically and abiotically, with important implications for life on Earth at each step (Barnum & Coates, 2022).

We were not able to find specific information on potassium hypochlorite degradation. However, as presented in the [Properties of the Substance](#) section [above](#), when sodium hypochlorite is mixed with water, it degrades to chlorate and chloride (Gray, 2014). The half-life of aqueous chlorine (an equilibrium mixture of hypochlorite and its conjugate hypochlorous acid) is affected by solution concentration, pH, temperature, light exposure, wind and presence of organic materials. As the concentration and temperature drop, the material becomes more stable (Abdul-Baki & Moore, 1979). For example, for a sodium hypochlorite aqueous solution with an active chlorine concentration of 100 g L⁻¹, the half-life is reported to be 800 days at 15 °C versus 0.079 days at 100 °C (Allied Chemical Corporation, 1949).

Table 1: Effects of temperature and concentration on stability of chlorine solutions.
Adapted from Allied Chemical Corporation (1949) cited in Abdul-Baki & Moore (1979).

Available chlorine (g L ⁻¹)	Temperature (C)			
	100	60	25	15
	Half-life (days)			
200	0.016	0.6	44	175
100	0.079	3.5	220	800
50	0.25	13	790	5000
25	0.63	28	1800	
5	2.5	100	6000	

The photolytic half-life of aqueous chlorine at the surface of a flat water body is about 12 min at pH 8, 37 min at pH 7, and 1 h at pH 6 when exposed as a horizontal water layer to solar irradiation of 1.05 kW m⁻², encountered on a sunny day in central Europe (Nowell & Hoigné, 1992). The effective wavelength region for significant sunlight absorption by aqueous chlorine is restricted to between about 320 and 340 nm.

In deeper mixed water columns, the dissolved organic carbon shields chlorine significantly by absorbing light. For example, Nowell and Hoigné (1992) showed that in a well-mixed column of eutrophic lake water with 4 mg L⁻¹ dissolved organic carbon, the photolytic half-life of chlorine over a mixed water column of 4 m depth is 20 times longer than at the surface, increasing from 12 min to about 240 min (pH 8). Based on these kinetic measurements, the photolytic lifetime of aqueous chlorine in cloud water during summer day-time (pH 4.5-5) will be on the order of magnitude of a couple of hours (Nowell & Hoigné, 1992).

The half-life of aqueous chlorine can be shortened by the presence of organic compounds or exposure to sunlight and wind. Researchers Vandepitte and Schowanek, cited by the Staff of the European Chemical Agency (2017), used a kinetic model to estimate half-lives for hypochlorite. They found a half-life of 20 minutes in surface water and sediment compared to 20 seconds in a sewer system due to the high content of organic materials in the sewage system. Amino acids and organic amines rapidly react with free chlorine to form organic chloramines. Similarly, Lee & Westerhoff (2009) reported that the addition of free chlorine into the natural organic matter isolate solutions and surface waters rapidly formed organic chloramines within 10 min. The organic nitrogen contents correlated with organic chloramines for both chlorination and chloramination.

Wong and Oatts (1984) measured dissolved organic matter and chlorine demand (using sodium hypochlorite) in estuarine water and seawater in the James River, Virginia and seawater at the mouth of Chesapeake Bay. Estuarine waters had higher dissolved organic carbon and chlorine demands than seawater. At a dose of 5 mg L⁻¹, in 23 h, about 90% of the added chlorine disappeared in estuarine waters, whereas, in seawater, only 60–75% of the chlorine had dissipated. At least two-thirds of the chlorine demand occurred in the first 5 h, with most of the chlorine demand attributed to the fraction. The fractions with lower molecular weights (< 1000 and 1000–10,000) always had a higher reactivity towards chlorine in terms of organic chlorine demand per unit weight of dissolved organic carbon (Wong & Oatts, 1984).

When applied as a disinfectant, chlorine is unstable, and it easily gets converted to chloride (Cl⁻) ions. The Cl⁻ ion is stable in soil environments and can move within and between ecosystems (Redon et al., 2011). Tens of species across all phyla can convert chloride to organic compounds (Öberg, 2002). Over 1000 chlorinated organic compounds have been identified. There is evidence that the concentration of methyl chloride and chloroform is higher in soil than in the ambient air, which suggests that such compounds are formed in the soil. Research in Sweden estimated the amount of chloride and organic chlorine in the soil at 29 and 104 kg Cl⁻ ha⁻¹, respectively (Öberg, 2002). Keppler (2000) provided evidence abiotic formation of chloromethane involving redox reactions with organic matter, iron and chloride takes place in soil.

Consideration of the organic chlorine pool is important in studies of overall chlorine cycling in terrestrial ecosystems as the theoretical average residence time calculated for total chlorine (inorganic and organic chlorine) was five times higher than that value for inorganic chlorine alone (Redon et al., 2011).

Environment and Human Health Effects

Evaluation Question #5: Discuss the probability of environmental contamination during manufacture, use, misuse or disposal of the substance [7 U.S.C. 6518(m)(3)].

Contamination during manufacture

Global chlorine production exceeded 101 million metric tons in 2023 and is projected to reach 129 million metric tons by 2030 (Statista, 2024). Chlorine is produced through the chlor-alkali process, which uses the electrolysis of sodium chloride to liberate chlorine (Crook & Mousavi, 2016). There are three primary electrolytic processes used to produce chlorine and caustic soda; the diaphragm cell process, the mercury cell process, and the membrane cell process (Crook & Mousavi, 2016).⁴

The chlor-alkali process is a very energy intensive industry, consuming nearly 10% of global electricity every year (Li et al., 2021). Using a life cycle analysis methodology, researchers found that the electrolysis stage is the main contributor to the environmental impacts from these processes due to energy consumption, causing 72-99.5% of the impacts (Garcia-Herrero et al., 2017). The mercury cell process is the least environmentally sustainable technology, closely followed by the diaphragm cell process (Garcia-Herrero et al., 2017).

The diaphragm cell process relies on the use of asbestos to separate the anode and cathode compartments (Dötzel & Schneider, 2002). In 2000, this process was responsible for 75% of the US production (Crook & Mousavi, 2016). As of 2024, two-thirds of the chlorine produced in the U.S. was produced without using asbestos (US EPA, 2024). In March 2024, the EPA announced a ban on asbestos imports for the chlor-alkali process and published a plan to phase out its use in the U.S. There are only eight chlor-alkali plants in the U.S. that still use asbestos diaphragms, and they were given a transition time to phase out the use of asbestos. For companies that plan to transition multiple facilities to non-asbestos membrane technology, the transition time is:

- 5 years to convert their first facility
- 8 years to convert their second
- 12 years to convert their third

The facilities will be required to certify their continued progress with EPA (US EPA, 2024).

Despite attempts to phase out the mercury cell process by European manufacturers, the process was still responsible for 55% of the production Western Europe in 2000 (Crook & Mousavi, 2016). The Minamata convention, signed by 128 nations in 2013, set a phaseout date of 2025 for the mercury process (Liu, 2023). The manufacture of chlorine using the mercury cell process results in mercury emissions. In addition, the manufacturing process produces gas emissions (Stringer & Johnston, 2001). The liberated chlorine is stored, while metallic sodium forms an amalgam with mercury (Kinsey et al., 2004). In the second stage, the amalgam is decomposed into metallic mercury, hydrogen, and metallic sodium, which reacts with water to form sodium hydroxide (caustic soda) (Kinsey et al., 2004). The global mercury emissions related to the chlor-alkali industry were 15.1 metric ton/year (UNEP - UN Environment Programme, 2019).

The membrane cell process employs a modification of the diaphragm cell method so that the diaphragm is a permselective ion-exchange membrane (Crook & Mousavi, 2016). This membrane inhibits the passage of chlorine ions but allows positively charged sodium ions to move through freely. It is superior to the other two methods in its energy efficiency and lack of harmful chemicals and is used to produce more than 90% of chlorine in Japan (Crook & Mousavi, 2016).

⁴ The Castner-Kellner mercury cell process, developed in 1892, is one of three electrolytic manufacturing processes used by the chlor-alkali sector to produce chlorine and caustic soda (Crook & Mousavi, 2016).

The membrane cell process compares positively to the other two processes from an energy efficiency perspective. According to a US Department of Energy report, the polymer electrolyte membranes process uses 2500 kWh/metric tonne (m.t.) of Cl₂ produced, versus 3700 kWh/m.t. Cl₂ for the mercury cell and 2900 for the diaphragm (Chlistunoff, 2007).

Contamination during use

The National Research Council's Safe Drinking Water Committee (1980) reviewed research related to surface water contamination from chlorination. They reported that experimental chlorination at a concentration of 2.3 µg L⁻¹ resulted in the presence of the following contaminants: a nucleoside, three purines, a pyrimidine, seven aromatic acids, and five phenolic compounds. The concentrations of these compounds ranged from a few tenths of a part per billion (ppb or µg L⁻¹) to 20 ppb (Jolley et al., 1978). Chlorination was also reported to result in aromatic compounds with concentrations varying between less than 1 µg L⁻¹ and 19 µg L⁻¹ (Munch et al., 1977).

There is no fire hazard present when storing sodium hypochlorite. The chemical is quite corrosive, however, and should be kept away from equipment that can be corroded. Sodium hypochlorite solution can lose 2 – 4% of its available chlorine content per month at room temperature. Therefore, manufacturers recommend a maximum shelf life of 60 to 90 days (Leidholdt, 2000).

In water, in the sewer and during sewage treatment, the degradation of hypochlorite is modelled by Vandepitte and Schowanek (1997) and the concentration is calculated to drop down to “zero” within a few minutes after release into the sewer (Escudero-Oñate, 2014; European Chemicals Agency, 2017).⁵ In soil, free active chlorine reacts rapidly with organic matter. The ultimate fate of hypochlorite in soil is its reduction to chloride. In the atmosphere, hypochlorous acid degrades photolytically to atomic chlorine and hydroxyl radicals OH° with a calculated half-life (Atkinson calculation) of 2750 hours, but there are indications that the half-life is much shorter (only a few hours).

Contamination during misuse and disposal

Cases of contamination during misuse of hypochlorites include:

- Not following recommended rates at application
- Improper disposal of containers
- Accidental spills
- Improper mixing of chemicals (household disinfectants) especially during COVID-19 pandemic (Lin et al., 2022)

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

The high solubility and negative charge of the chloride ion mean that its distribution is controlled by the water cycle. Water transports chloride from soils to streams and groundwater, though if evaporation is high enough, chloride can be brought to the soil surface (Öberg, 2002).

The EPA safe drinking water levels allow for use of higher doses of potassium hypochlorite in irrigation water and for equipment cleaning as long as the residual chlorine at the irrigation outlet does not exceed the federal limit. Those levels are unlikely to have adverse biological and chemical interactions in the agroecosystem.

Effects of hypochlorite on soil and plants

Lonigro et al. (2017) evaluated the effects of variable residual chlorine concentrations (0, 0.2, 10, and 40 mg Cl L⁻¹) on the accumulation of extractable organo-halogenated compounds in soils and lettuce leaf tissues. The first trial was conducted using two different soil types (sandy and silty-clay soil). The treatment in the silty-clay soil watered with 10 mg Cl L⁻¹ (2.5 times the allowed limit in drinking water)

⁵ The model for hypochlorite degradation developed by Vandepitte and Schowanek (1997) is referenced regularly in documents. However, we were unable to locate a copy of the European report from which it originates.

showed double the concentration of extractable organo-halogenated compounds compared to the control, while the same treatment in the sandy soil was not statistically different from the untreated control. The plants grown under the higher chlorine concentrations showed typical symptoms of salt stress (e.g., chlorosis, leaf necrosis, and reduced crop yield) since the first watering with chlorinated water, which resulted in non-marketable plants. Root system damage was correlated to the amount of chlorine concentration in the irrigation water.

In soil, free active chlorine reacts rapidly with organic matter to produce compounds such as trihalomethanes (Gallard & von Gunten, 2002). Among organic compounds, methoxyl, phenolic, and ketonic structural groups are the most reactive groups to chlorine (Hanna et al., 1991). The ultimate fate of hypochlorite in soil is its reduction to chloride.

Effects of hypochlorite on microorganisms

Yu et al. (2023) conducted an experiment to evaluate the effect of irrigation water with a low concentration of chlorine on the soil-wheat microbiome system. They analyzed the influence on the soil microbial community using metagenomics.⁶ After 14 days of continuous chlorine treatment, there were no significant lasting effects on soil microbial community diversity and composition either in the rhizosphere or in bulk soil. Metabolic functions of the rhizosphere microbial community were slightly affected by continuous chlorine treatment but recovered to the original status. Similarly, the abundance of several resistance genes changed by 7 days and recovered by 14 days. In rhizosphere soil, among the top 50 high abundant genes, a total of 10 and 9 resistance genes were significantly affected by chlorine at 7 d and 14 d, respectively. Principal coordinates analysis of rhizosphere soil at 7 d showed that the abundance of resistance genes in the control was clustered and separated from those in the 1 mg L⁻¹ chlorine treatment along the principal coordinates analysis axis (explaining 93.5% of the variation). The bulk soil had no significant differences between treatments.

Effects of hypochlorite on soil invertebrates

Bezchlebová et al. (2007) studied the effects of short-chain chlorinated paraffins (64% chlorine content) on invertebrates (*Eisenia fetida*, *Folsomia candida*, *Enchytraeus albidus*, *Enchytraeus crypticus*, *Caenorhabditis elegans*). *F. candida* was identified as the most sensitive organism with LC50 and EC50 values of 5733 and 1230 mg kg⁻¹, respectively. A predicted no effect concentration of 5.28 mg kg⁻¹ was estimated for the soil environment.

Effects of hypochlorite on fish

Brooks & Bartos (1984) carried out laboratory bioassays to determine the acute toxicity of monochloramine, dichloramine, hypochlorous acid, and hypochlorite ion to emerald shiners (*Notropis atherinoides*), channel catfish (*Ictalurus punctatus*), and rainbow trout (*Salmo gairdneri*). They used four exposure regimes typical of chlorination schedules at electric power plants. Power plant operators commonly chlorinate cooling water to control odors. The researchers exposed fish to a single 15-minute, 30-minute, and 120-minute period, as well as four 30-minute periods. Based on median lethal concentrations (LC50s):

- Hypochlorous acid was the most toxic.
- This was followed closely by the solution dominated by dichloramine.
- Monochloramine and hypochlorite ion solutions had one third to one quarter of the toxicity of the other two substances.

Emerald shiners were the most sensitive species to the four forms of chlorine (Brooks & Bartos, 1984). The fish were most tolerant of chlorine during short-duration exposures and least tolerant during the continuous 120-minute exposures. The authors concluded that the differences in toxicity posed by different chlorine forms highlight the need to consider fish species, total residual chlorine and duration of exposure when determining chlorination regimes and regulations (Brooks & Bartos, 1984).

⁶ Metagenomics is the study of the structure and function of entire nucleotide sequences isolated and analyzed from all the organisms (typically microbes) in a bulk sample. Metagenomics is often used to study a specific community of microorganisms, such as those residing on human skin, in the soil or in a water sample (Segre, 2024).

Cooke and Shreer (2001) reviewed the literature to determine the effects of chlorine used by power plants as a biopesticide on some Great Lake fish species. They found that the sensitivity of different species to chlorine varies widely. In general, fish avoid high levels of chlorine when they detect the source point. However, elevated temperature magnifies the toxic effects of chlorine on fish. When chlorination is used at temperatures near the thermal maxima, but not sufficiently high to exclude fish, high mortality rates can be expected. Most of the fish that lose equilibrium during exposure do not survive. Fish exposed to sublethal levels of chlorine become lethargic and often gulp air, frequently suffering from increased predation pressures from birds and other fish. Additionally, hematological and biochemical disturbances, and potentially irreversible gill damage, may impair the lifetime fitness of fish exposed to chlorine (Cooke & Schreer, 2001).

Effects of hypochlorite on other freshwater organisms

Batley et al. (2021) analyzed chlorine's effects on different groups of freshwater organisms including insects, crustaceans, bivalves, macrophytes and fish. All the bioassays they reviewed were "acute tests," where a lethal or adverse sublethal effect occurred after exposure to a chemical for a short period of time. They suggested revised default guideline values for both hypochlorite and chloramine in freshwater using a species sensitivity distribution of toxicity data. The revised total residual chlorine values for 95% species protection were 7 µg Cl L⁻¹ for hypochlorite and 9 µg Cl L⁻¹ for chloramine. The most sensitive species were mayfly nymphs (*Baetis harrisoni*) and the cladocerans *Ceriodaphnia dubia*, with 96- and 24-h LC50 (50% lethal effect concentration) values of 4.4 and 6 µg Cl L⁻¹, respectively, and *Daphnia magna*, with a 48-h LC50 of 17 µg Cl L⁻¹. Bivalves appeared to be the next most sensitive group, and fish were the least sensitive. They described these values as conservative, given that they were based on flow-through systems that prolong the exposure period, which will result in greater effects than tests undertaken with exposure conditions that mimic the field situations (Batley et al., 2021).

Evaluation Question #7: Discuss and summarize findings on whether the use of the petitioned 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)].

While we did not find information on potassium hypochlorite specifically, the EPA reached the following conclusion in its 2012 calcium and sodium hypochlorite registration review (Lindheimer et al., 2012):

"All environmental fate and ecological effects data requirements for sodium and calcium hypochlorite have been satisfied since the Registration Standard was issued in 1986. Upon reevaluating these data, EPA has concluded that the currently registered uses of the hypochlorites will not result in unreasonable adverse effects to the environment."

Chloride in soils and sediments can be alkylated as a halide ion to produce volatile halogenated organic compounds through the oxidation of organic matter by an electron acceptor such as Fe(III) (Keppler et al., 2000).

The use of potassium hypochlorite instead of sodium hypochlorite might be less harmful to the soil from salt accumulation and soil salinization standpoints. Sodium is a phytotoxic element when present in high concentrations, and soil sodicity caused by an excessive accumulation of exchangeable sodium ions destroys soil structure and contributes to detrimental effect on plant growth conditions (Verma et al., 2024). In contrast, potassium is a primary macronutrient that does not cause soil sodicity if present in higher amounts. In addition, the maintenance of plant growth and yield development relies on the activation of enzymatic processes in the cytoplasm, which requires an appropriate ratio of potassium ion (K⁺) to sodium ion (Na⁺) (Verma et al., 2024).

Evaluation Question #8: Describe and summarize any reported effects upon human health from use of the petitioned substance [7 U.S.C. 6517(c)(1)(A)(i), 7 U.S.C. 6517(c)(2)(A)(i) and 7 U.S.C. 6518(m)(4)].

The NOP regulations allow potassium hypochlorite application rates that are consistent with drinking water standards for humans (NOSB, 2019), which is 1-2 ppm, and not to exceed free chlorine of 4 ppm (EPA, 2015). These levels are unlikely to be harmful to human health or the environment (EPA, 2015).

As of 2016, the Environmental Protection Agency has not established a reference concentration for chlorine inhalation (EPA, 2016). An older reference dose of 0.1 mg/kg-day was reported by EPA's IRIS (Integrated Risk Information System) system in 1994 (IRIS, 1994). The California Office of Environmental Health Hazard Assessment (OEHHA) set the reference exposure level for chlorine at 210 micrograms per cubic meter ($\mu\text{g}/\text{m}^3$) for acute (1 hour) exposure and 0.2 $\mu\text{g}/\text{m}^3$ for chronic (continuous exposures for up to a lifetime) exposure (Monserrat, 2016).

Potassium hypochlorite is a powerful oxidizing agent that produces highly toxic fumes of chlorine gas upon heating or contact with acids (Sax & Lewis, 2012). We did not find reports on the effect of potassium hypochlorite on human health, specifically. Chlorine is the active ingredient in hypochlorites.

Since sodium hypochlorite (bleach) is chemically similar to potassium hypochlorite and can be used for the same purposes, we included sodium hypochlorite in this report. Chlorine is the active ingredient in hypochlorites. A previous technical report covered chlorine in detail in 2011 (see [Chlorine/Bleach, Crops](#)). As mentioned in *Evaluation Question #3 above*, chlorine reacts with natural organic matter to produce a variety of toxic disinfection by-products. These harmful reactions can be avoided by removing natural organic matter present in water through physical/chemical treatment processes, such as enhanced coagulation and activated carbon filtration (Sedlak & von Gunten, 2011).

Hypochlorites pose human health and environmental concerns under some circumstances (NOP, 2011). Ingestion of hypochlorites may be dangerous to human health. Using rats as a proxy for humans, Bruch (2007) conducted single-dose toxicity studies in rats using 1.1% sodium hypochlorite solutions. He found that the LD50 for rats (the dose required to be lethal in 50% of tested animals) was 290 mg kg⁻¹ body weight from an oral dose and 33.3 mg kg⁻¹ from an intravenous dose (Bruch, 2007). According to a potassium hypochlorite material safety data sheet, the LD50 through oral ingestion (using rats) is 3-5 g kg⁻¹ while the LD50 through dermal toxicity (using rabbits) >10 g kg⁻¹ (Environmental Compliance Resources, LLC, 2013).

Human exposure to higher concentrations of hypochlorites may result in a wide range of reactions and damage, including (Chung et al., 2022; Peck et al., 2011):⁷

- irritation or damage to the skin, eyes, and the respiratory tract
- kidney damage
- diarrhea
- vomiting
- inflammation
- burns
- perforation
- stricture
- death

Sodium hypochlorite concentrations used in medical sanitization and as a medical antiseptic are usually in the range of 0.5-2% (Stanford Environmental Health & Safety, 2024), a range that presents extremely low toxicity hazards if contacted by humans (Peck et al., 2011). For example, Chung et al. (2022) reviewed medical studies on the health effects of sodium hypochlorite and concluded that health impacts resulting from long-term occupational or environmental exposure to low sodium hypochlorite concentrations were rare. Chung et al. (2022) cited a case of intravenous infusion of 12 mL of 5% sodium hypochlorite that led to diffuse alveolar hemorrhage. Intradermal injection of 5.25% NaOCl produced immediate hemorrhage and edema lasting hours after injection (Chung et al., 2022; Peck et al., 2011). Large volume ingestion of bleach, typically associated with suicide attempts, can result in severe health problems including death. In one such case, a 66-year-old female ingested a large quantity of 5.25% sodium hypochlorite leading to severe esophageal and airway burns along with perforation of the gastroesophageal junction, bilateral pneumothorax and pneumoperitoneum. The case was complicated by severe metabolic acidosis and cardiopulmonary arrest, and resulted in the woman's death (Kuiper et al., 2005).

⁷ The authors did not state what constituted "higher concentrations."

Report Authorship

The following individuals were involved in research, data collection, writing, editing, and/or final approval of this report:

- Ashraf Tubeileh, Associate Professor, California Polytechnic State University
- Jarod T Rhoades, Standards Manager, OMRI
- Peter O. Bungum, Research and Education Manager, OMRI
- Ashley Shaw, Technical Research and Administrative Specialist, OMRI

All individuals are in compliance with Federal Acquisition Regulations (FAR) Subpart 3.11 – Preventing Personal Conflicts of Interest for Contractor Employees Performing Acquisition Functions.

References

- Abdul-Baki, Aref. A., & Moore, G. M. (1979). Seed disinfection with hypochlorites: A selected literature review of hypochlorite chemistry and definition of terms. *Journal of Seed Technology*, 4(1), 43–56.
- Aftalion, F. (1991). *A History of the International Chemical Industry*. University of Pennsylvania Press.
- Allied Chemical Corporation. (1949). *Chlorine bleach solutions* (Bulletin No. 14). Solvay Technical and Engineering Service.
- Andrés, C. M. C., Pérez de la Lastra, J. M., Juan, C. A., Plou, F. J., & Pérez-Lebeña, E. (2022). Hypochlorous acid chemistry in mammalian cells – Influence on infection and role in various pathologies. *International Journal of Molecular Sciences*, 23(18), 10735. <https://doi.org/10.3390/ijms231810735>
- Bandte, M., Rodriguez, M. H., Schuch, I., Schmidt, U., & Buettner, C. (2016). Plant viruses in irrigation water: Reduced dispersal of viruses using sensor-based disinfection. *Irrigation Science*, 34(3), 221–229. <https://doi.org/10.1007/s00271-016-0500-1>
- Barnum, T. P., & Coates, J. D. (2022). The biogeochemical cycling of chlorine. *Geobiology*, 20(5), 634–649. <https://doi.org/10.1111/gbi.12513>
- Batley, G. E., Adams, M. S., & Simpson, S. L. (2021). *Short-term guideline values for chlorine in freshwaters*. <https://doi.org/10.1002/etc.4984>
- Bezchlebová, J., Černohlávková, J., Kobetičová, K., Lána, J., Sochová, I., & Hofman, J. (2007). Effects of short-chain chlorinated paraffins on soil organisms. *Ecotoxicology and Environmental Safety*, 67(2), 206–211. <https://doi.org/10.1016/j.ecoenv.2006.12.015>
- Boecker, D., Zhang, Z., Breves, R., Herth, F., Kramer, A., & Bulitta, C. (2023). Antimicrobial efficacy, mode of action and in vivo use of hypochlorous acid (HOCl) for prevention or therapeutic support of infections. *GMS Hygiene and Infection Control*, 18, Doc07. <https://doi.org/10.3205/dgkh000433>
- Brooks, A. S., & Bartos, J. M. (1984). Effects of free and combined chlorine and exposure duration on rainbow trout, channel catfish, and emerald shiners. *Transactions of the American Fisheries Society*, 113(6), 786–793. [https://doi.org/10.1577/1548-8659\(1984\)113<786:EOFACC>2.0.CO;2](https://doi.org/10.1577/1548-8659(1984)113<786:EOFACC>2.0.CO;2)
- Bruch, M. K. (2007). Toxicity and safety of topical sodium hypochlorite. In *Disinfection by Sodium Hypochlorite: Dialysis Applications* (Vol. 154, pp. 24–38). Karger. https://d1wqtxts1xzle7.cloudfront.net/49844756/Effectiveness_of_sodium_hypochlorite_in_20161024-12793-10uwcg-libre.pdf?1477356761=&response-content-disposition=inline%3B+filename%3DEffectiveness_of_Sodium_Hypochlorite_in.pdf&Expires=1724020870&Signature=Db9iwW5T1efuUGhkBV2jGHXXdGv1TY6EM2eADL8T9lhNDal2eDPpUNB~mjZ859jcs1kXQxlxO4OX54iB7mXtf-KvX-DzNfQahH4Cvf3JKB0Io6BC9dD9YYLy91eLrtZ7wN2slOw7Xs4SGI7UtgZg-7FaUO4Fil0brtusc-GXnLbEowF9pA4myCW1WFh-GCQldHqx8wECOz8smPmalkiWDoD41IZsNLricwM6S1SAaKJ6oG8Z-SDKPwYne7rgE5k8ixviwTCmBmjhSF-CZAgwxiNymn93OgS2QrRgT6X~nR1w~HYDDPxwMNBs7ZVjQ-TzRODtD3kZE5iDrks7tpg_&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA#page=35
- CAMEO Chemicals. (2024). *Potassium hypochlorite solution*. CAMEO Chemicals | NOAA. <https://cameochemicals.noaa.gov/chemical/4315>
- Cayanan, D. F., Dixon, M., Zheng, Y., & Llewellyn, J. (2009). Response of container-grown nursery plants to chlorine used to disinfect irrigation water. *HortScience*, 44(1), 164–167. <https://doi.org/10.21273/HORTSCI.44.1.164>

- Chlistunoff, J. (2007). *Advanced Chlor-Alkali Technology* (p. 100) [Project report]. Los Alamos National Laboratory.
https://www1.eere.energy.gov/manufacturing/industries_technologies/imf/pdfs/1797_advancedcotechnologyfinal.pdf
- Chung, I., Ryu, H., Yoon, S.-Y., & Ha, J. C. (2022). Health effects of sodium hypochlorite: Review of published case reports. *Environmental Analysis, Health and Toxicology*, 37(1), e2022006. <https://doi.org/10.5620/eaht.2022006>
- Cooke, S. J., & Schreer, J. F. (2001). Additive effects of chlorinated biocides and water temperature on fish in thermal effluents with emphasis on the great lakes. *Reviews in Fisheries Science*, 9(2), 69–113. <https://doi.org/10.1080/20016491101717>
- Copes, W. E., & Ojiambo, P. S. (2021). Efficacy of Hypochlorite as a Disinfectant Against Fungal Pathogens in Agricultural and Horticultural Plant Production: A Systematic Review and Meta-Analysis. *Phytopathology*®.
<https://doi.org/10.1094/PHTO-05-20-0201-R>
- Crook, J., & Mousavi, A. (2016). The chlor-alkali process: A review of history and pollution. *Environmental Forensics*, 17(3), 211–217.
<https://doi.org/10.1080/15275922.2016.1177755>
- Datnoff, L. E., Kroll, T. K., & Lacy, G. H. (1987). Efficacy of chlorine for decontaminating water infested with resting spores of *Plasmodiophora brassicae*. *Plant Disease*, 71(8), 734–736. <https://doi.org/10.1094/PD-71-0734>
- Deborde, M., & von Gunten, U. (2008). Reactions of chlorine with inorganic and organic compounds during water treatment – Kinetics and mechanisms: A critical review. *Water Research*, 42(1), 13–51. <https://doi.org/10.1016/j.watres.2007.07.025>
- Donnermair, M. M., & Blatchley, E. R. (2003). Disinfection efficacy of organic chloramines. *Water Research*, 37(7), 1557–1570.
[https://doi.org/10.1016/S0043-1354\(02\)00522-5](https://doi.org/10.1016/S0043-1354(02)00522-5)
- Dötzel, O., & Schneider, L. (2002). Non-asbestos Diaphragms in Chlor-Alkali Electrolysis. *Chemical Engineering & Technology*, 25(2), 167–171. [https://doi.org/10.1002/1521-4125\(200202\)25:2<167::AID-CEAT167>3.0.CO;2-0](https://doi.org/10.1002/1521-4125(200202)25:2<167::AID-CEAT167>3.0.CO;2-0)
- Enviro Tech Chemical Services. (2014). *Enviro Klor* (p. 11). Enviro Tech Chemical Services.
- Environmental Compliance Resources, LLC. (2013). *K Klor material safety data sheet*. Environmental Compliance Resources.
https://s3-us-west-1.amazonaws.com/agrian-cg-fsl-production/pdfs/K_KLOR_MSDS.pdf
- EPA. (2015). *National primary drinking water regulations*. Environmental Protection Agency.
https://www.epa.gov/sites/default/files/2015-11/documents/howepargulates_cfr-2003-title40-vol20-part141_0.pdf
- EPA. (2016). *Chlorine: 7782-50-5*. US Environmental Protection Agency. <https://www.epa.gov/sites/default/files/2016-09/documents/chlorine.pdf>
- Escudero-Oñate, C. (2014). *Survey of sodium and calcium hypochlorite*. The Danish Environmental Protection Agency.
https://prodstoragehoeringspo.blob.core.windows.net/9cbcb23-83c1-4ff5-92bc-183a263dfe86/38%20-%20Final_LOUS%20%20hypochlorites.pdf
- European Chemicals Agency. (2017, January). *Regulation (EU) No 528/2012 concerning the making available on the market and use of biocidal products. Evaluation of active substances assessment report. Active chlorine released from sodium hypochlorite*. European Chemicals Agency. https://dissemination.echa.europa.eu/Biocides/ActiveSubstances/1391-02/1391-02_Assessment_Report.pdf
- Fisher, P. R., Argo, W. R., Hong, C., Huang, J., Looper, A., Wieggers, D., Vetanovetz, R., & Zheng, Y. (2008, June). Using sodium and calcium hypochlorite for water treatment. *Greenhouse Management*, 28(6), 21–25.
- Gallard, H., & von Gunten, U. (2002). Chlorination of natural organic matter: Kinetics of chlorination and of THM formation. *Water Research*, 36(1), 65–74. [https://doi.org/10.1016/S0043-1354\(01\)00187-7](https://doi.org/10.1016/S0043-1354(01)00187-7)
- Garcia-Herrero, I., Margallo, M., Onandía, R., Aldaco, R., & Irabien, A. (2017). Environmental challenges of the chlor-alkali production: Seeking answers from a life cycle approach. *Science of The Total Environment*, 580, 147–157.
<https://doi.org/10.1016/j.scitotenv.2016.10.202>
- Ghernaout, D. (2017). Water treatment chlorination: An updated mechanistic insight review. *Chemistry Research Journal*, 2(4), 125–138.
- Goraj, W., Pytlak, A., Kowalska, B., Kowalski, D., Grządziel, J., Szafranek-Nakoneczna, A., Gałązka, A., Stępniewska, Z., & Stępniewski, W. (2021). Influence of pipe material on biofilm microbial communities found in drinking water supply system. *Environmental Research*, 196, 110433. <https://doi.org/10.1016/j.envres.2020.110433>
- Gray, N. F. (2014). Chapter Thirty-One – Free and Combined Chlorine. In S. L. Percival, M. V. Yates, D. W. Williams, R. M. Chalmers, & N. F. Gray (Eds.), *Microbiology of Waterborne Diseases (Second Edition)* (pp. 571–590). Academic Press.
<https://doi.org/10.1016/B978-0-12-415846-7.00031-7>

- Hanna, J. V., Johnson, W. D., Quezada, R. A., Wilson, M. A., & Lu, X. Q. (1991). Characterization of aqueous humic substances before and after chlorination. *Environmental Science & Technology*, 25(6), 1160–1164. <https://doi.org/10.1021/es00018a022>
- How, Z. T., Kristiana, I., Buseti, F., Linge, K. L., & Joll, C. A. (2017). Organic chloramines in chlorine-based disinfected water systems: A critical review. *Journal of Environmental Sciences*, 58, 2–18. <https://doi.org/10.1016/j.jes.2017.05.025>
- IRIS, U. E. P. A. (1994, June 1). *Chlorine CASRN 7782-50-5* [Reports & Assessments]. https://iris.epa.gov/ChemicalLanding/&substance_nmbr=405
- Jolley, R., Jones, G., Pitt, W., & Thompson, J. (1978). Chlorination of organics in cooling waters and process effluents. In *Water Chlorination: Environmental Impact and Health Effects* (pp. 105–138). Ann Arbor Science Publishers, Inc.
- Juan, C. A., Pérez de la Lastra, J. M., Plou, F. J., & Pérez-Lebeña, E. (2021). The Chemistry of Reactive Oxygen Species (ROS) Revisited: Outlining Their Role in Biological Macromolecules (DNA, Lipids and Proteins) and Induced Pathologies. *International Journal of Molecular Sciences*, 22(9), Article 9. <https://doi.org/10.3390/ijms22094642>
- Keppeler, F., Eiden, R., Niedan, V., Pracht, J., & Schöler, H. F. (2000). Halocarbons produced by natural oxidation processes during degradation of organic matter. *Nature*, 403(6767), 298–301. <https://doi.org/10.1038/35002055>
- Kinsey, J. S., Anscombe, F. R., Lindberg, S. E., & Southworth, G. R. (2004). Characterization of the fugitive mercury emissions at a chlor-alkali plant: Overall study design. *Atmospheric Environment*, 38(4), 633–641. <https://doi.org/10.1016/j.atmosenv.2003.09.059>
- Kirmeyer, G. J. (2004). *Optimizing chloramine Treatment*. AWWA Research Foundation, American Water Works Association, Denver, Co, USA. American Water Works Association.
- Kuiper, J. W., Groeneveld, A. B. J., Slutsky, A. S., & Plötz, F. B. (2005). Mechanical ventilation and acute renal failure. *Crit Care Med*, 33(6), 1408–1415.
- Lee, W., & Westerhoff, P. (2009). Formation of organic chloramines during water disinfection – chlorination versus chloramination. *Water Research*, 43(8), 2233–2239. <https://doi.org/10.1016/j.watres.2009.02.009>
- Leidholdt, R. (2000). Chlorine – “Special agent” for disinfecting water. *Opflow*, 26(6), 40–43. <https://doi.org/10.1002/j.1551-8701.2000.tb02248.x>
- Li, K., Fan, Q., Chuai, H., Liu, H., Zhang, S., & Ma, X. (2021). Revisiting Chlor-Alkali Electrolyzers: From Materials to Devices. *Transactions of Tianjin University*, 27(3), 202–216. <https://doi.org/10.1007/s12209-021-00285-9>
- Lin, G.-D., Wu, J.-Y., Peng, X.-B., Lu, X.-X., Liu, Z.-Y., Pan, Z.-G., Qiu, Z.-W., & Dong, J.-G. (2022). Chlorine poisoning caused by improper mixing of household disinfectants during the COVID-19 pandemic: Case series. *World Journal of Clinical Cases*, 10(25), 8872. <https://doi.org/10.12998/wjcc.v10.i25.8872>
- Lindheimer, T., Mottl, N., Malish, S., Gowda, S., Bays, D., Shamim, N., Henson, W., Wormell, L., & Ross, P. (2012). *Na & ca hypochlorite summary document registration review* (Chemical Safety and Pollution Prevention, p. 41). Environmental Protection Agency. <https://downloads.regulations.gov/EPA-HQ-OPP-2012-0004-0002/content.pdf>
- Liu, A. (2023). Advances in Chlor-Alkali Technologies. *Chemical Engineering*, 130(9), 37–39.
- Lonigro, A., Montemurro, N., & Laera, G. (2017). Effects of residual disinfectant on soil and lettuce crop irrigated with chlorinated water. *Science of The Total Environment*, 584–585, 595–602. <https://doi.org/10.1016/j.scitotenv.2017.01.083>
- Mattice, J. S., & Zittel, H. E. (1976). Site-Specific Evaluation of Power Plant Chlorination. *Journal (Water Pollution Control Federation)*, 48(10), 2284–2308.
- Monserat, L. (2016, January 18). *Oehha acute, 8-hour and chronic reference exposure level (rel) summary* [Text]. OEHHA. <https://oehha.ca.gov/air/general-info/oehha-acute-8-hour-and-chronic-reference-exposure-level-rel-summary>
- Morris, J. (1975). *Formation of halogenated organics by chlorination (a review)* (EPA-600/1-75-002; p. 154). Office of Research and Development, U.S. Environmental Protection Agency.
- Munch, D., Feige, M., & Brass, H. (1977). The analyses of purgeable compounds in the national organic monitoring survey by gas chromatography/mass spectrometry. *Water Quality in the Distribution System*, Paper 3A-6, 5 pp.
- National Research Council (US) Safe Drinking Water Committee. (1980). The chemistry of disinfectants in water: Reactions and products. In *Drinking Water and Health* (Vol. 2). National Academies Press (US). <https://www.ncbi.nlm.nih.gov/books/NBK234591/>

- NOP. (2011, January 31). *Technical evaluation report: Chlorine/bleach*. Washington D.C.: National Organic Program. <https://www.ams.usda.gov/sites/default/files/media/Chlorine%20%20TR%202011.pdf>
- NOP. (2024, March 20). NOP 5026: Guidance. *The use of chlorine materials in organic production and handling*. National Organic Program. <https://www.ams.usda.gov/sites/default/files/media/5026.pdf>
- Norman, T. S., Harms, L. L., & Looyenga, R. W. (1980). The Use of Chloramines To Prevent Trihalomethane Formation. *Journal (American Water Works Association)*, 72(3), 176–180.
- Norton, C. D., & LeChevallier, M. W. (1997). Chloramination: Its effect on distribution system water quality. *Journal AWWA*, 89(7), 66–77. <https://doi.org/10.1002/j.1551-8833.1997.tb08260.x>
- NOSB. (2019, October 25). *Formal recommendation. From: National Organic Standards Board (NOSB). To: The National Organic Program (NOP). Sunset reviews – Crops 2021*. National Organic Program. <https://www.ams.usda.gov/sites/default/files/media/CS2021SunsetReviews.pdf>
- Nowell, L. H., & Hoigné, J. (1992). Photolysis of aqueous chlorine at sunlight and ultraviolet wavelengths—I. Degradation rates. *Water Research*, 26(5), 593–598. [https://doi.org/10.1016/0043-1354\(92\)90232-S](https://doi.org/10.1016/0043-1354(92)90232-S)
- Öberg, G. (2002). The natural chlorine cycle – fitting the scattered pieces. *Applied Microbiology and Biotechnology*, 58(5), 565–581. <https://doi.org/10.1007/s00253-001-0895-2>
- Peck, B., Workeneh, B., Kadikoy, H., Patel, S. J., & Abdellatif, A. (2011). Spectrum of sodium hypochlorite toxicity in man – Also a concern for nephrologists. *NDT Plus*, 4(4), 231–235. <https://doi.org/10.1093/ndtplus/sfr053>
- Raudales, R. E., Parke, J. L., Guy, C. L., & Fisher, P. R. (2014). Control of waterborne microbes in irrigation: A review. *Agricultural Water Management*, 143, 9–28. <https://doi.org/10.1016/j.agwat.2014.06.007>
- Rayson, M. S., Altarawneh, M., Mackie, J. C., Kennedy, E. M., & Dlugogorski, B. Z. (2010). Theoretical study of the ammonia–hypochlorous acid reaction mechanism. *The Journal of Physical Chemistry A*, 114(7), 2597–2606. <https://doi.org/10.1021/jp9088657>
- Reckhow, D. A., Ostendorf, D. W., & Billa, M. E. (1990). Fate and transport of combined residual chlorine in small stream. *Journal of Environmental Engineering*, 116(6), 1125–1142. [https://doi.org/10.1061/\(ASCE\)0733-9372\(1990\)116:6\(1125\)](https://doi.org/10.1061/(ASCE)0733-9372(1990)116:6(1125))
- Redon, P.-O., Abdelouas, A., Bastviken, D., Cecchini, S., Nicolas, M., & Thiry, Y. (2011). Chloride and Organic Chlorine in Forest Soils: Storage, Residence Times, And Influence of Ecological Conditions. *Environmental Science & Technology*, 45(17), 7202–7208. <https://doi.org/10.1021/es2011918>
- Rodriguez, M. H., Bandte, M., Gaskin, T., Fischer, G., & Büttner, C. (2018). Efficacy of electrolytically-derived disinfectant against dispersal of *Fusarium oxysporum* and *Rhizoctonia solani* in hydroponic tomatoes. *Scientia Horticulturae*, 234, 116–125. <https://doi.org/10.1016/j.scienta.2018.02.027>
- Sax, N., & Lewis, R. (2012). Potassium hypochlorite 7778-66-7. In *Sax's Dangerous Properties of Industrial Materials* (pp. 1–2). John Wiley & Sons, Ltd. <https://doi.org/10.1002/0471701343.sdp46911>
- Sedlak, D. L., & von Gunten, U. (2011). The chlorine dilemma. *Science*, 331(6013), 42–43. <https://doi.org/10.1126/science.1196397>
- Segre, J. (2024, November 1). *Metagenomics*. National Human Genome Research Institute. <https://www.genome.gov/genetics-glossary/Metagenomics>
- Snell, J. A., Jandova, J., & Wondrak, G. T. (2022). Hypochlorous acid: From innate immune factor and environmental toxicant to chemopreventive agent targeting solar uv-induced skin cancer. *Frontiers in Oncology*, 12, 887220. <https://doi.org/10.3389/fonc.2022.887220>
- Staff of the European Chemical Agency. (2017). *Active chlorine released from sodium hypochlorite. Assessment report. Regulation (eu) no 528/2012 concerning the making available on the market and use of biocidal products*. European Chemicals Agency. <https://echa.europa.eu/documents/10162/0f87765c-1bb2-9bb0-6b41-c8b54841dfd5>
- Stanford Environmental Health & Safety. (2024). Sodium hypochlorite (bleach). *Stanford University*. <https://ehs.stanford.edu/reference/sodium-hypochlorite-bleach>
- Statista. (2024). *Chlorine global market volume 2030*. Statista.Com. <https://www.statista.com/statistics/1310477/chlorine-market-volume-worldwide/>
- Stringer, R., & Johnston, P. (2001). *Chlorine and the Environment: An Overview of the Chlorine Industry*. Springer Science & Business Media.

- UNEP - UN Environment Programme, U. N. (2019). *Global mercury assessment 2018* (p. 59). Chemicals and Health Branch, UNEP. <https://www.unep.org/topics/chemicals-and-pollution-action/pollution-and-health/heavy-metals/mercury/global-mercury-2>
- US EPA, O. (2024, March 18). *Biden-Harris Administration finalizes ban on ongoing uses of asbestos to protect people from cancer* [News Release]. <https://www.epa.gov/newsreleases/biden-harris-administration-finalizes-ban-ongoing-uses-asbestos-protect-people-cancer>
- Vandepitte and Schowanek (1997). *The model for hypochlorite degradation developed by Vandepitte and Schowanek (1997) is referenced regularly in documents. However, we were unable to locate a copy of the European report from which it originates.*
- Verma, P., Ghosh Bag, A., Verma, S., & PA, A. (2024). Amelioration of Salt Affected Soil with Potassium Fertilization: A Review. *Communications in Soil Science and Plant Analysis*, 0(0), 1–23. <https://doi.org/10.1080/00103624.2024.2419991>
- Winter, J., Ilbert, M., Graf, P. C. F., Özcelik, D., & Jakob, U. (2008). Bleach activates a redox-regulated chaperone by oxidative protein unfolding. *Cell*, 135(4), 691–701. <https://doi.org/10.1016/j.cell.2008.09.024>
- Wong, G. T. F., & Oatts, T. J. (1984). Dissolved organic matter and the dissipation of chlorine in estuarine water and seawater. *Water Research*, 18(4), 501–504. [https://doi.org/10.1016/0043-1354\(84\)90160-X](https://doi.org/10.1016/0043-1354(84)90160-X)
- Yu, Y., Zhang, Q., Zhang, Z., Xu, N., Li, Y., Jin, M., Feng, G., Qian, H., & Lu, T. (2023). Assessment of residual chlorine in soil microbial community using metagenomics. *Soil Ecology Letters*, 5(1), 66–78. <https://doi.org/10.1007/s42832-022-0130-x>