Chlorine dioxide for water treatment and sanitation

Chlorine dioxide is a highly effective water disinfectant, capable of killing a wide range of pathogens, and removing contaminants. This POSTnote examines the ability of chlorine dioxide in water treatment, the technologies around its use, and implications for water-scarce areas.

Overview

- ☐ Chlorine dioxide is a highly effective disinfectant against waterborne pathogens
- ☐ Only 0.7% of the total freshwater on earth is available for use
- ☐ Climate change and the water crisis is leading to a strain on the availability of safe drinking water
- ☐ Increased consumption of unsafe drinking water can put strain on healthcare facilities, leading to more disease outbreaks
- ☐ Several pathogens are capable of causing serious disease through water contamination, including cholera and dysentery

Background

Chlorine dioxide was first discovered by Sir Humphrey Davy in 1811, when the gas was released upon reacting potassium chlorate with sulphuric acid, (Simpson, et al., 1993). Since the 1940s it has been used primarily in the paper industry as a bleaching agent, and in the treatment of drinking water due to its high efficacy as a broad-spectrum biocide, (Gordon & Rosenblatt, 2005). Chlorine dioxide was first used to combat phenols, and sensory issues (tastes and odours) caused by chlorophenols and algae, in the Niagara Falls water treatment plant (WTP) in 1944, (Gray, 2014). Chlorine dioxide is typically manufactured from the reaction between sodium chlorite and hydrochloric acid in water, as shown in the equation below, (Lenntech, 2023):

$$NaClO_2 + HCl + H_2O -> ClO_2 + NaCl + H_2O$$

In 1993, the World health Organisation (WHO) issued guidance on the maximum residual and contaminant concentration for chlorine dioxide and chlorite, respectively, at 0.8mg/L and 1mg/L each, (Gray, 2014). This was updated in 2008, to include chlorate, with maximum concentrations for chlorite and chlorate in drinking water at the point of use (consumer's tap) not to exceed 0.7mg/L each. A maximum residual for chlorine dioxide has not been re-established due to the disinfectant breaking down into chlorite and chloride upon ingestion, (WHO, 2016). Although these disinfectant by-products are not carcinogenic, they can lead to anaemia, and have the potential to cause damage to the nervous system, hence the strict regulations in place to control their concentrations in drinking water, (Reuter & Lastoskie, 2021). Chlorine dioxide has a high level of safety in water treatment, with studies finding that 40mg/L did not produce any subchronic oral health issues in rabbits, (Jefri, et al., 2022).

How chlorine dioxide treatment works

Chlorine dioxide is a highly selective disinfectant, that reacts in water by the process of oxidation. Due to this selective action, chlorine dioxide does not produce the carcinogenic, chlorinated by-products typically associated with chlorine disinfection, (Gordon & Rosenblatt, 2005). Chlorine dioxide is highly unstable as a gas, and so generation of this disinfectant always occurs on site at the water treatment plant, where a redox reaction takes place between sodium chlorite and hydrochloric acid in water to produce a dilute aqueous solution, (Palmer, 2021). Chlorine dioxide is effective at a wide temperature and pH range, from 4-10, and microorganisms are unable to develop resistance, (Yee, et al., 2020). Chlorine dioxide is a very powerful oxidant, capable of killing many pathogens at very low concentrations. Table 1 below gives the chlorine dioxide concentration required to kill several important human pathogens.

Table 1. Chlorine dioxide concentration required to kill important human pathogens. Data taken from (Chatuev & Peterson, 2010); (Gatlabayan, et al., 2023); (Shams, et al., 2011); (Trinetta, et al., 2013); (Rubio-Casillas & Campra-Madrid, 2021); (Sanekata, et al., 2010); (Chechet, et al., 2022); (Yevstafieva, et al., 2023)

Pathogen	ClO_2 CT-value
Bacillus anthracis	30 mg/L $^{-1}$
MRSA	10 mg/L $^{-1}$
Yersinia pestis	0.5 mg/L $^{-1}$
Stachybotrys bisbyi	33.6 mg/L $^{-1}$
COVID-19	0.2-10 mg/L $^{-1}$
Influenza A virus	2.5 mg/L $^{-1}$
Rabies virus	300 mg/L $^{-1}$
Trichuris skrjabini (hookworm)	200 mg/L $^{-1}$

Chlorine dioxide is not only highly effective against unicellular microorganisms, but has also been found to reduce nematode populations by at least 90% with concentrations as low as 0.73 mg/L with a contact time of 30 minutes. Nematodes can ingest many bacterial and viral pathogens including *Salmonella* and *Shigella*, and protect them from disinfectants, this also allows the pathogens to survive within their nematode host for up to 24 hours, enabling them to travel through a water system and potentially cause infection in humans, (Kos, et al., 2020).

Prioritisation of clean, safe drinking water

Water is essential to all life on Earth. The Earth is nearly 75% water, and yet only 2.8% is freshwater, and of this, a tiny 0.7% is available for use in the form of ground- and surface waters, (Elsaie, et al., 2023). Water is a precious resource, with access to an adequate and safe water supply considered a basic human right, recognised by the UN General Assembly

in 2010, however, according to the WHO and UNICEF, up to 13% of the global population does not have access to a clean water supply, (Kumar, et al., 2020), and at least 4.5 billion people do not have access to safely managed sanitation practices, (Magana-Arachchi & Wanigatunge, 2020).
Safe drinking water has a profoundly positive impact on human health, reducing the risk of exposure to waterborne pathogens. Waterborne infections are exceedingly common, with at least 1.5 million children dying every year from diarrhoeal diseases in low-middle income countries, (Cabral, 2010), and an estimated 1.7 billion deaths annually due to poor water quality, (Kumar, et al., 2020). As such, control of these pathogens, especially in drinking water, is of the utmost importance.

Control of water pathogens

Chlorine dioxide breaks through the cell walls of microorganisms and interrupts the normal functioning of cellular processes, causing irreparable damage to DNA, and disrupting amino acid production, leading to death of the cell. As it acts directly on cells while they are inactive, very low concentrations are required to kill microbes, and they cannot develop resistance, (Lenntech, 2023). This gas is also highly effective against complex microbes including amoebas, parasites, cysts, protozoa, and biofilms. The latter of which can form protective layers on a surface, such as the inner lining of water pipes, and harbour pathogenic bacteria and fungi, protecting them from environmental stressors, (Mehta, 2021). The majority of waterborne pathogens are found in biofilms, with very few species being "free-living", as these biofilms can provide a more reliable source of nutrients, protect the pathogen from environmental stressors and disinfectants, and can allow for the pathogen to be disseminated in the water more easily, (Nocker, et al., 2014). Pathogens can enter a watercourse though biological or chemical contamination, surface runoff during floods, or can be native to that environment.
Table 2. below gives the chlorine dioxide concentration required to kill common waterborne pathogens.

Table 2. Chlorine dioxide concentration required to kill common waterborne pathogens. Data taken from (Sohn, et al., 2024); (Isomoto, et al., 2006); (Erickson & Ortega, 2006); (Georgiou & Kotze, 2023); (Smigic, et al., 2010); (Tomas-Callejas, et al., 2012); and (Burrows & Renner, 1999)

Pathogen	ClO_2 CT value
Acinetobacter baumannii	5 mg/L^{-1}
Campylobacter	40 mg/l^{-1}
E. coli	125 mg/L^{-1}
Helicobacter pylori	5 mg/L^{-1}
Salmonella spp.	3 mg/L^{-1}
Shigella spp.	0.5 mg/L^{-1}
Vibrio cholerae	40 mg/L^{-1}
Naegleria fowleri	0.36 mg/L^{-1}
Calicivirus	0.16 mg/L^{-1}
Cryptosporidium	12.9 mg/L^{-1}

Several waterborne pathogens are considered ubiquitous in water environments, including *Legionella, Shigella, Cryptosporidium, Acanthamoeba,* and *Vibrio cholerae*.

Legionella are waterborne gram-negative rod-shaped bacteria that can cause serious disease and a potentially fatal pneumonia. There are eight species of *Legionella* that are considered pathogenic, however, up to 98% of all disease in the US is caused by *L. pneumophila*, (Donohue, et al., 2023). *L. pneumophila* is an opportunistic pathogen, typically acquired through exposure in communities, hospitals, and other health care settings. Two forms of the disease associated with *Legionella* exist: legionnaire's disease (severe infection) and Pontiac fever (mild infection), (Nisar, et al., 2020). *Legionella* are endemic in freshwater systems, moist soils, and are also a major component of biofilms and can colonise pipelines with many commercial water systems including air conditioning units, water towers, vegetable misters, and spas, providing optimum conditions for *Legionella* growth, (Taylor, et al., 2009). These biofilms can be dislodged when water is pumped through the system, providing a near constant opportunity for contamination, (Taylor, et al., 2009).

Shigella are gram-negative, nonmotile rod-shaped bacteria and is the causative agent of bacillary dysentery, or shigellosis. Dysentery is a primarily human disease; however, it can also occur in other captive primates. It is most commonly associated with crowded environments, such as shanty-towns and slums, and with poor sanitation and water hygiene, (Nisa, et al., 2020). Four pathogenic strains of *Shigella* have been deemed clinically important to health. These are *S. flexneri, S. sonnei, S. dysenteriae,* and *S. boydii*, (Nisa, et al., 2020). *S. flexneri* is most prevalent in Low- and Middle Income (LMIC) countries, whereas *S. sonnei* is mostly found in developed countries, where it is mainly encountered through schools and daycare settings. *S. boydii* is most typically found in Bangladesh and India, (Muzembo, et al., 2023). In these areas there are an estimated 5 million cases of shigellosis that require hospitalisation, and up to 600,000 deaths annually, (Percival & Williams, 2014). *Shigella* are transmitted through waters contaminated with waste or untreated drinking water, usually via the faecal-oral route. Humans are considered the only natural reservoir of *Shigella spp.*; however, samples have been isolated from several other sources, including birds, watercourses, insects, milk, and free-living amoeba, (Nisa, et al., 2020). Typical symptoms of shigellosis are fever, abdominal colic, and watery or bloody diarrhoea. Severe infections can cause malnutrition, encephalopathy, haemolytic uremic syndrome, impaired cognitive development, and in some cases may be fatal, (Muzembo, et al., 2023).
Antibiotic resistance has been identified in several *Shigella* outbreaks in recent years, with Peru reporting up to 60% of *Shigella* isolates being resistant to common antibiotics, and up to 85% of isolates from China being multi-drug resistant, (Nisa, et al., 2020).

Cryptosporidium parvum is a parasite that is responsible for severe abdominal infections in both humans and animals. Domestic ruminants, especially cattle, act as the main reservoir hosts for *Cryptosporidium* and contamination of water with sewage and effluent from livestock has been linked to several outbreaks of disease in human, (DuPont, et al., 1995). Although ruminants are considered the main reservoir for this parasite, *C. parvum* exhibits a lack of host specificity, allowing for zoonotic transmission with relative ease, (Laurent, et al., 1999). Serological testing has found that over 15% of the entire US population have been infected with *C. parvum* at one point or another, while almost 100% of people living in tropical regions tested positive for *C. parvum* antibodies, (DuPont, et al., 1995). Infection with *C. parvum* manifests as diarrhoea and gastroenteritis, with symptoms occurring after an incubation period of 2-14 days. These symptoms include nausea, vomiting, abdominal cramps, weight loss, fever, and loss of appetite. In immunocompromised individuals, further symptoms include wasting syndrome, jaundice, and pancreatitis, due to the blocking of the bile duct with oocysts, (Laurent, et al., 1999). Oocysts are resistant to most disinfectants, including chlorine and as such can cause outbreaks even in treated drinking water. Chlorine dioxide has been found to effectively inactivate *C. parvum* oocysts at concentrations of at least 500mg/L-^{1}, much higher than the dose rate typically used in conventional drinking water treatment, (Chauret, et al., 2001).

Acanthamoeba is an opportunistic protozoan pathogen, and is found in all water sources, including sea water, swimming pools, tap water, natural thermal waters, ponds, rivers and sediments, and also in soils, dust, and the air. It has also been isolated from nasal mucosa in healthy people, (Wang, et al., 2023). Other potential sources of infection include vegetation, hospital environments including surgical instruments, sterile saline solutions, dialysis machines, contact lenses, eyewash stations, and ventilation systems, (Gomes de Lacerda & Lira, 2021).

Vibrio are gram-negative rod-shaped bacteria and contain several species that are capable of causing disease in humans. This includes *V. cholerae*, the causative agent of cholera; *V. parahaemolyticus* which causes food poisoning in Southeast Asia and Japan; *V. damsela* which causes wound infections, and *V. fluvialis, V. hollisae*, and *V. mimicus* which all cause fever, diarrhoea, and gastroenteritis, (Percival & Williams, 2014). Cholera is primarily a waterborne disease; however foodborne infections can occur through consumption of contaminated seafood. The disease spreads via person-to-person transmission, usually via the faecal-oral route, and is associated with poor hygiene, and a lack of access to sanitation and adequate water supplies, (Taylor, et al., 2015). The first six of the seven cholera pandemics were caused by classical *V. cholera*, with the last attributed to the El Tor biotype, (Percival & Williams, 2014). The seventh pandemic started in 1961 and continues to the present day in Bangladesh, and exhibits high seasonality, with epidemics occurring in both the pre- and post-monsoon seasons, (Islam, et al., 2020). Cholera outbreaks have been suggested to be influenced by coastal environmental conditions, such as sea surface temperature and height, and the concentration of oceanic chlorophyll, (Islam, et al., 2020). However, they mainly occur in the wake of emergency situations, such as floods and earthquakes, and in refugee camps where the appropriate infrastructure may be challenged, (Taylor, et al., 2015). Clinical signs of infection present with gastroenteritis, with several other species of *Vibrio* presenting with wound infections or sepsis on rare occasions. With regard to cholera, it is estimated that 3-5 million people contract this disease every year, with roughly 100,000 deaths occurring in Asia, most commonly in the Ganges Delta, (Baker-Austin, et al., 2018).

Improvement of water quality

The quality of water for both household and recreational use can be vastly improved by the application of disinfectants and appropriate water treatment chemicals. Disinfection of water is essential to remove chemical, biological, and organic contaminants, including pathogens and unwanted minerals and metals, (Jefri, et al., 2022). Chlorination is the most common form of water treatment due to its relatively low cost; however, it can lead to the formation of carcinogenic by-products, including trihalomethanes and haloacetic acids, (Reuter & Lastoskie, 2021). Chlorine dioxide is a suitable alternative to chlorination, with studies showing a reduction in trihalomethanes and haloacetic acids by 85% and 60%, respectively, in drinking water treatment plants, (Volk, et al., 2002). Chlorine dioxide has been found to effectively reduce *E. coli* counts in drinking water systems up to 3,500 metres from the point of dosing to below detection limits, (Al-Hamzah, et al., 2019). In emergency situations, four common WASH interventions are typically implemented: provision or repair of water supplies; treatment of water at the central or household level; provision of sanitation solutions; promotion of body and environmental hygiene, (Branz, et al., 2017). With regard to the treatment of emergency drinking water, several methods may be utilised, including boiling, disinfection tablets, such as chlorine dioxide or chlorine tablets, iodine, UV radiation in combination with thermal disinfection, and the use of lemon juice, (WHO, 2004).

Disinfection by-products

Due to the selective nature of chlorine dioxide, it does not produce carcinogenic disinfection by-products typically associated with chlorine disinfection. It also does not react with organic matter to produce high levels of aldehydes, ketones, and other such harmful compounds produced when organic matter is oxidised in water, (Gordon & Rosenblatt, 2005). When chlorine dioxide interacts with bromide ions in water it can lead to the formation of hydrobromous acid, which in turn can release bromoform, (Li, et al., 1996). In waters with high levels of total organic carbon by-products associated with chlorine dioxide disinfection are chlorite and chlorate, the latter of which is gaining attention from its use in pesticides, may be produced, (Gray, 2014). Chlorine dioxide does not produce an odour in water, nor is it associated with taste issues that can be given off with chlorine use. As such, not only is this chemical extensively used in water treatment, but it is also being used to control pathogens in fresh produce including soft fruits and flowers, (Ran, et al., 2019).

Impact of climate change and chlorine dioxide on water use

Climate change and global warming is estimated to have a dramatic effect on climate stability, leading to more extreme changes in the water cycle, causing an increase in both the severity and frequency of extreme weather events, such as tropical storms, floods, and droughts, (Gray, 2014). Water scarcity can lead to higher concentrations of pathogens in a water supply, which when the availability of water increases, either during floods or heavy rainfall after droughts, become "water-washed" pathogens. These pathogens often include diarrhoeal diseases transmitted via the faecal-oral route, such as cholera, and dysentery, (Cairncross & Feachem, 2019). Rising global temperatures is leading to water scarcity in many countries, predominantly those around the equator. Water shortages are estimated to exceed 40% by 2030, affecting billions of people, (Manju & Sagar, 2017).

Potential of desalination plants for scarce water supplies

Water scarcity is caused by a lack of safe, clean water, and may be due to environmental pollution, water locked up in glaciers and ice caps, or rising sea levels. Water scarcity can be divided into two categories: physical and economic, (*fig. 1.*). Physical water scarcity pertains to the lack of adequate water resources, while economic water scarcity relates to a lack of infrastructure available to access the water in that particular region, (Gude, 2017).

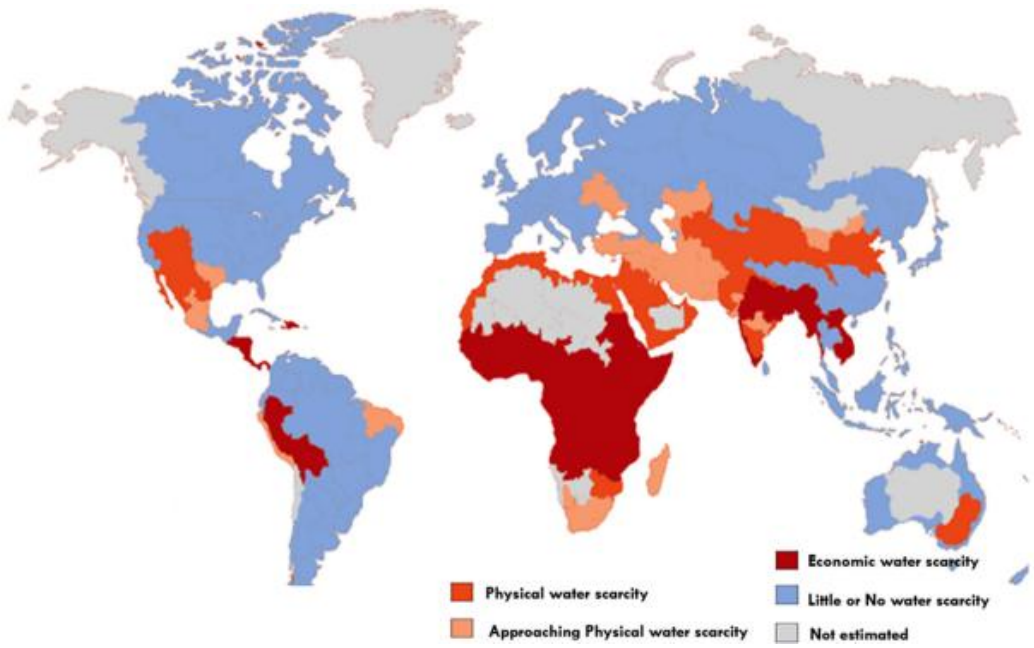

Figure 1. different types of water scarcity around the world, image taken from (Gude, 2017)

Many countries that are commonly affected by droughts have access to both sea- and brackish waters, which are ideal for desalination, (Gude, 2017). As of 2020, over 20,000 desalination plants and projects were in place around the world, providing clean, safe water to upwards of 300 million people every day, (Eke, et al., 2020). The vast majority of drinking water in the Middle East, particularly Saudi Arabia, is obtained through the desalination of seawater from the Red Sea and the Arabian Gulf, (Al-Hamzah, et al., 2019). Desalination is the process of removing dissolved solids from water sources, either by boiling off the freshwater, membrane filtration, and reverse osmosis. These processes use large amounts of heat and electrical energy, so efficient renewable energy supplies are essential to ensure that desalination plants can be a sustainable source of clean water, (Manju & Sagar, 2017).

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