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DISINFECTION BY-PRODUCTS IN DRINKING WATER SYSTEMS WITH REFERENCE TO THE ALGERIAN CONTEXT

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ABSTRACT

Chemical disinfection is crucial for drinking water safety but inevitably produces disinfection by-products (DBPs) via reactions between oxidants and natural organic matter (NOM), halides, and nitrogenous compounds. These reactions yield diverse carbonaceous and nitrogenous DBPs, including regulated trihalomethanes (THMs) and haloacetic acids (HAAs), as well as numerous unregulated species with potentially greater cytotoxic and genotoxic effects. Globally, DBP formation varies with natural organic matter characteristics, bromide content, oxidant dose, pH, temperature, and contact time. High mineralization and halide levels favor brominated DBPs, typically more toxic than chlorinated analogues. Regulatory indicators such as THMs and HAAs account for only a fraction of total halogenated by-products, many of which are poorly characterized.

Epidemiological evidence links long-term DBP exposure to elevated risks of bladder, colorectal, and other cancers, along with potential reproductive and developmental effects. In Algeria, where chlorination dominates and surface waters with high organic and inorganic loads are increasingly used, studies reveal high chlorine demand, significant THM formation, and elevated total organic halogen (TOX) levels. Spatial variability exists, with northern waters dominated by chlorinated DBPs and southern/coastal waters enriched in brominated species due to bromide. Rising colorectal, bladder, and gastric cancer incidences further suggest that DBP exposure may be an environmental co-factor warranting investigation.

Technical strategies for DBP control include enhanced coagulation, optimized oxidation/chlorination conditions, pre-oxidation (e.g., potassium permanganate or ozone), and multi-barrier treatments combining advanced processes and biological activated carbon. Evaluating these approaches in light of Algerian water characteristics underscores the need for integrated monitoring of regulated and emerging DBPs, treatment optimization, and stronger linkage between water quality management and public health surveillance.

Keywords: Disinfection By-Products, Drinking water treatment, Toxicological risk, DBP mitigation, Algerian surface water.

INTRODUCTION

Access to safe drinking water is universally recognized as a fundamental human right and a cornerstone of public health. However, ensuring this access remains a global challenge, particularly in developing countries facing resource constraints, rapid population growth, and uneven infrastructure development. The degradation of natural water resources, driven by urban expansion, agricultural intensification, and industrial discharges, further complicates the situation. These pressures are especially acute in arid and semi-arid regions such as African countries, where water scarcity is compounded by declining water quality (Remini, 2024). In Algeria, as in many other countries, these challenges necessitate the use of robust water treatment strategies to ensure compliance with sanitary standards.

Among the different steps in water treatment, disinfection is critical for safeguarding the microbiological quality of drinking water. Chlorination remains the most widely employed disinfection method worldwide because it is simple, cost-effective, and highly efficient against a broad spectrum of pathogenic microorganisms (Achour and Chabbi, 2014; WHO, 2017). In Algeria, chlorine-based disinfection is routinely applied in both urban and rural systems, particularly where surface water sources such as rivers, dams, and reservoirs dominate. Given their high susceptibility to microbial contamination, these sources require effective disinfection to reduce the risk of waterborne disease outbreaks.

However, the benefits of chlorination are tempered by the unintended formation of disinfection by-products (DBPs). These compounds arise from reactions between chlorine and naturally occurring organic matter, as well as with inorganic ions such as bromide and iodide (Krasner, 2009; Villanueva et al., 2015). A wide range of DBPs has been identified, with trihalomethanes (THMs) and haloacetic acids (HAAs) being the most studied and regulated (Achour et al., 2009; Mouly et al., 2008; USEPA, 2011). Other DBPs, such as haloacetonitriles, haloketones, chloropicrin, and chloral hydrate, also occur, although they are less frequently monitored despite potential toxicological importance.

Reported concentrations of DBPs vary widely across regions and seasons, reflecting differences in source water quality, climate, and treatment practices. The extent and composition of DBP formation depend on multiple factors, including precursor concentration and type, chlorine dose, contact time, pH, temperature, and ionic composition (Minear and Amy, 1996), making their control a persistent challenge for water utilities.

Research over the past decades has linked long-term exposure to elevated THM levels with increased risks of bladder and colorectal cancer, as well as with reproductive and developmental effects (Richardson et al., 2007; Helte et al., 2025). In response, international regulatory bodies have established strict guideline values. For example, the

U.S. Environmental Protection Agency (EPA, 2010) enforces a maximum contaminant level of 80 µg/L for total THMs, while the World Health Organization (WHO) provides guidance values for each individual compound (WHO, 2017).

In Algeria, chlorination remains the cornerstone of drinking water disinfection, but evidence increasingly highlights its unintended consequence: the formation of DBPs. Studies have documented exceedances of international guideline values in several regions, especially during summer months when elevated temperatures and organic matter levels favor DBP formation (Achour and Guergazi, 2002; Achour et al., 2014). These exceedances are most often associated with surface water supplies and with variability in operational practices across treatment facilities. Furthermore, disparities in infrastructure, monitoring capacity, and resource availability complicate the establishment of consistent nationwide control strategies. Although Algeria has begun regulating chlorination and monitoring THM levels, available data remain too limited to fully assess exposure patterns or population-level health risks.
While large-scale epidemiological investigations are lacking in Algeria, international toxicological and epidemiological evidence raises legitimate concerns. Chronic exposure to DBPs has been associated with carcinogenic, hepatotoxic, nephrotoxic, and endocrine-disrupting effects. These risks underscore the urgency of strengthening DBP control strategies and surveillance in Algerian water systems.

Against this background, the present study reviews the scientific evidence on disinfection by-products in drinking water, with a particular focus on DBPs in Algeria. It examines the factors influencing their occurrence, the levels reported across different regions and seasons, and the potential health implications. By situating Algerian findings within the broader international context, this work aims to inform future regulatory, technical, and research efforts to reduce DBP exposure and improve water safety.

DISINFECTION OF DRINKING WATER

Ensuring the microbiological safety of drinking water requires reliable disinfection strategies capable of eliminating or inactivating pathogenic microorganisms. Historically, outbreaks of cholera, typhoid, and other enteric diseases highlighted the necessity of systematic disinfection in water treatment systems (Cutler and Miller, 2005). Today, a variety of methods is employed, including chlorination, ozonation, ultraviolet (UV) irradiation, and the use of chloramines. Among these, chlorination has achieved the widest application worldwide because of its low cost, ease of implementation, and ability to provide a persistent disinfectant residual throughout the distribution system (Hrudey and Charrois, 2012; ACC, 2019).

Alternative disinfectants, while effective under certain conditions, face practical limitations. Ozone, for instance, is a powerful oxidant with proven efficacy against protozoa such as Cryptosporidium but is costly and unstable, requiring on-site generation (Von Gunten, 2003). UV irradiation is increasingly used in high-income countries for its ability to inactivate a broad range of microorganisms without forming chemical by-products, yet it lacks residual protection and is sensitive to water turbidity (Hull et al.,

2019). Chloramines, often used as secondary disinfectants in North America, provide longer-lasting residuals but are weaker primary disinfectants and can generate emerging by-products such as nitrosamines (Krasner et al., 2013).

In Algeria, the choice of disinfectant is shaped by economic and infrastructural constraints. Surface waters from rivers, reservoirs, and dams constitute significant drinking water sources, and their high vulnerability to microbial pollution necessitates robust disinfection practices (Achour, 2015; Guessas et al., 2024).
The country relies increasingly on surface water from dams, because groundwater reserves are insufficient and often degraded. This surface water is frequently of average to poor quality, with pollution of anthropogenic origin and high levels of organic matter, ammonia, and bromides (Achour et al., 2009, Harrat and Achour, 2010). For this reason, chemical oxidants such as chlorine, ozone, and potassium permanganate are quite often used in treatment plants across the country.

To contextualize chlorination within the broader spectrum of disinfectants, Table 1 summarizes the main methods, highlighting their advantages, disadvantages, and relevance to Algerian water systems.

Table 1: Comparison of major drinking water disinfection methods and their applicability in Algeria

Disinfectant	Main Advantages	Main Disadvantages	Residual in Distribution	Applicability in Algeria
Chlorine	Low cost, effective against bacteria and viruses, provides residual	Formation of DBPs (THMs, HAAs), taste/odor issues	Yes	Widely used in both urban and rural systems
Ozone	Strong oxidant, effective against protozoa (e.g., Cryptosporidium)	High cost, no residual, complex technology	No	Limited use due to cost and infrastructure constraints
UV	Effective inactivator of bacteria, viruses, protozoa; no DBPs	No residual, requires good water quality (low turbidity)	No	Limited; feasible only in small-scale or pilot projects
Chloramines	More stable residual than chlorine, fewer regulated DBPs	Less effective against pathogens, potential formation of nitrosamines	Yes	Not commonly applied in Algeria
Chlorine dioxide	Effective against viruses and protozoa, less THM formation	Generates chlorite and chlorate by-products, requires careful control	Limited	Not applied due to operational complexity

In most Algerian stations, chlorination remains the universal final step in disinfection. It is carried out either with chlorine gas in large plants or with sodium hypochlorite, often produced on site through electrolysis of brine (Achour, 2012). For example, at the Ain Tinn plant in Mila, sodium hypochlorite is produced in situ using industrial salt, a low-cost solution that avoids the risks of chlorine gas storage (Achour and Chabbi, 2017). Chlorination ensures complete elimination of pathogens and provides a lasting residual effect in the distribution network. However, this stage faces challenges because raw waters, such as those from the Beni Haroun dam, have high chlorine demand, which leads to large reagent consumption and the formation of undesirable by-products such as trihalomethanes (Achour et al, 2014).

Some advanced stations have introduced more sophisticated oxidation strategies. The oxidation and disinfection strategy at Ain Tinn illustrates a more advanced multi-barrier approach compared to conventional Algerian plants. It combines pre-ozonation, clarification, biological filtration, post-ozonation, granular activated carbon filtration, and final chlorination. The Ain Tinn plant and the Oued Athmenia plant, both in the Wilaya of Mila, are equipped with ozonation processes. At Ain Tinn, pre-ozonation is used at the beginning of treatment, replacing pre-chlorination in order to avoid the formation of chlorinated by-products. This step, with a dose of about 1.5 g/m³, oxidizes organic matter, iron, manganese, and algae, while also improving coagulation and clarification. Post-ozonation is applied after biofiltration, with a higher dose of 2.5 g/m³ and a longer contact time, to ensure the oxidation of residual organic matter, pesticides, algal toxins, and to improve taste and odor. In this station, potassium permanganate is also applied in pretreatment to precipitate manganese and iron and to control algae (Achour and Chabbi, 2017).

The overall Algerian practice therefore relies on the universal application of chlorine for final disinfection, while some stations, like Ain Tinn and Oued Athmenia, demonstrate the introduction of ozone and permanganate to address the limitations of chlorination alone. This reflects an ongoing effort to balance strong disinfection with the need to minimize risks to public health and improve the overall quality of drinking water.

FORMATION, CLASSIFICATION AND OCCURRENCE OF DBPS

Disinfection-by-products (DBPs) form when any water disinfectant (chlorine, chloramines, chlorine dioxide, ozone, UV or combinations/AOPs) reacts with natural organic matter (NOM), inorganic precursors (bromide, iodide, ammonia) or anthropogenic contaminants in source water (Richardson et al., 2007; Xiao et al., 2024). Chlorination is the most widely used disinfectant worldwide and therefore the best studied. Rook (1974) first recognized that haloforms (now called trihalomethanes, THMs) can form from the reaction of chlorine with natural organic material.

Chemical pathways of DBP formation

Several chemical pathways lead to DBP formation (Forster et al., 2025). Electrophilic halogenation and substitution occur at aromatic or aliphatic sites in NOM, producing organohalogenated DBPs such as THMs and haloacetic acids (HAAs). Oxidation and chain cleavage of NOM molecules generate smaller oxygenated organics such as aldehydes, ketones, and short-chain carboxylic acids. Halide oxidation, for example the conversion of bromide to hypobromous acid (HOBr), leads to brominated or iodinated DBPs, which are often more toxic than their chlorinated analogues. Nitrosation and amine-oxidation reactions, especially under chloramination, form nitrogenous DBPs such as N-nitrosodimethylamine (NDMA) (Krasner, 2009; Richardson et al., 2007). Fig. 1 provides a schematic representation of the formation process of DBPs in water.

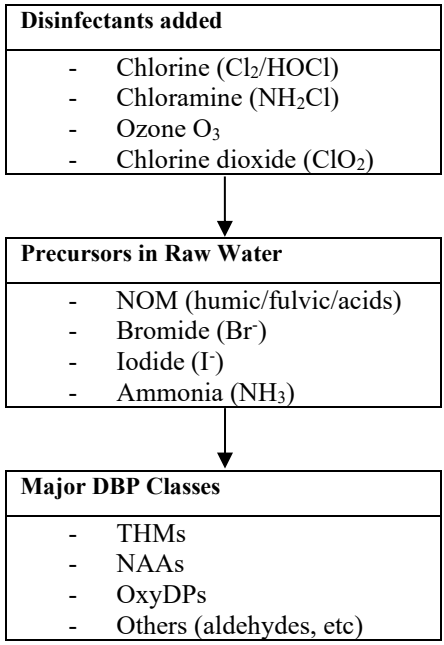


Figure 1: Schematic representation of DBPs formation in water

Classification of DBPs

Since their discovery, more than 600 DBPs have been chemically characterized. This number represents only a fraction of the total organic halogen (TOX) produced in disinfected water. However, Chen et al. (2024) compiled a database of DBPs reported in the literature since 1974. Fewer than 7% have been verified, while most are halogenated, with brominated DBPs as common as chlorinated ones. Proposed DBPs are mainly phenolic or highly unsaturated structures linked to lignin and tannins.

DBPs are generally classified as follows according to their volatility and halogen content (Lei et al. 2023).

- Volatile organohalogenated DBPs primarily include the four regulated trihalomethanes (THMs): chloroform, bromodichloromethane, dibromochloromethane, and bromoform.
- Non-volatile organohalogenated DBPs comprise haloacetic acids (HAAs), haloacetonitriles, haloketones, and chloral hydrate.
- In contrast, non-halogenated DBPs consist of oxygenated compounds such as aldehydes (e.g., formaldehyde, acetaldehyde), ketones, short-chain carboxylic acids (e.g., formic and acetic acid), and small alcohols.
- Nitrosamines, notably N-nitrosodimethylamine (NDMA), are also included in this category due to their nitrogen-containing structures (Bond et al., 2012).
- Research on DBP formation mechanisms has focused on identifying precursors, intermediates, and kinetics to predict new DBP classes and inform strategies for precursor removal and treatment optimization.

A review by Forster et al. (2025) examines eight DBP groups:(trihalomethanes (THMs), haloacetic acids (HAAs), haloketones (HKs), haloacetaldehydes (HALs), haloacetonitriles (HANs), haloacetamides (HAMs), halonitromethanes (HNMs), and nitrosamines (NAs). Key precursors include phenolic, β-dicarbonyl, and oxopentadioic moieties in humic NOM, as well as amino acids. Specific pathways include HAN formation via aldehyde chloramination, HAM formation via HAN hydrolysis, and HNM formation via amine oxidation/halogenation or humic substance nitration/halogenation in the presence of nitrite. Preozonation enhances HNM yields. Nitrosamines primarily arise from chloramine reactions (via dichloramine and dissolved oxygen) or from N,N-dimethylsulfamide.

Influence of disinfectants and operational parameters

Chemical disinfectants most frequently applied in drinking water treatment include chlorine, ozone, permanganate, chlorine dioxide, and chloramine. Both their own properties and those of the disinfection by-products (DBPs) they generate, which in turn affect environmental behavior, toxicity, and health outcomes influence their interaction with water.

The formation of DBPs is controlled by water characteristics, such as total organic carbon (TOC), bromide concentration, pH, temperature, ammonia, and alkalinity, as well as treatment practices, including the amount and type of disinfectant used, contact duration, and whether natural organic matter (NOM) is removed before disinfection (WHO, 2000). The type of disinfectant applied has a decisive influence on the DBP spectrum (Minear and Amy, 1996).

When chlorine is present as hypochlorous acid (HOCl) or hypochlorite ion (OCl–), it can oxidize bromide into hypobromous acid (HOBr) or hypobromite ion (OBr–). HOCl is generally a stronger oxidizing agent, while HOBr tends to be a more potent halogenating species. Together, they react with NOM to generate a wide spectrum of DBPs.

The proportions of different DBPs depend strongly on TOC, bromide, and chlorine levels. For example, THMs may appear as chloroform, bromoform, bromodichloromethane (BDCM), or dibromochloromethane (DBCM). HAAs can occur in up to nine chlorinated or brominated forms, and HANs also present in multiple variants (Sinha et al., 2021). While chlorinated DBPs are usually dominant, high-bromide waters often shift the balance toward brominated compounds. Despite extensive study, many chlorine-related DBPs remain unidentified, leaving a portion of total organic halogens unaccounted for. Another relevant pathway is the generation of chlorate (ClO3–), particularly in concentrated hypochlorite solutions.

Ozonation in bromide-containing waters generates bromate as a major inorganic DBP, along with aldehydes and low-molecular-weight carboxylic acids (Minear and Amy, 1996).

Chloramination generally reduces THM and HAA concentrations compared with chlorination, but favors the formation of nitrogenous DBPs such as NDMA, and may contribute to nitrification within distribution systems.

Chlorine dioxide treatment predominantly yields chlorite and chlorate, as well as oxidized organic by-products.

Ultraviolet (UV) disinfection alone produces very few halogenated DBPs. However, UV and UV-based advanced oxidation processes (AOPs) can generate carbonyl compounds and short-chain acids, and may transform natural organic matter (NOM) into precursors for other DBPs (WHO, 2006; Krasner, 2009; Liu, 2014; Richardson and Postigo, 2015).

Operational variables such as disinfectant type and dose, contact time, pH, and temperature further modulate DBP formation (Kalita et al., 2024). Higher pH and temperature generally accelerate reaction kinetics, enhancing DBP production, while disinfectant type determines the relative formation of halogenated versus nitrogenous DBPs. Additionally, ammonia and other nitrogenous compounds contribute to nitrogenous DBPs (N-DBPs) such as nitrosamines under chloramination.

In general, elevated NOM concentrations, higher bromide levels, and warmer conditions are consistently associated with increased DBP formation potential.

Reported concentrations worldwide

Reported concentrations of disinfection by-products (DBPs) vary substantially across regions, reflecting differences in source water quality, disinfectant practices, and regulatory frameworks.

Trihalomethanes (THMs) are among the most prevalent DBPs in drinking water, with average total THM (TTHM) levels of approximately 11.7 µg/L across European Union countries (Evlampidou et al., 2020). In France, 95% of people are supplied with chlorinated tap water. Trihalomethanes (THMs) are the only regulated CBP in France. Current and past mean exposure of the French population to THMs was estimated at 11.7 $\mu g \cdot L^{-1}$ and 17.3 $\mu g \cdot L^{-1}$ (Corso et al., 2018).

In contrast, monitoring data from the United States and several Asian and African cities indicate higher levels, frequently ranging from several tens to more than 100 µg/L (Villanueva et al., 2023). In the United States, TTHM values commonly fall in the low tens of $\mu g \cdot L^{-1}$, but individual utilities or seasonal peaks may reach or exceed regulatory limits (Karim et al., 2020).

Measured concentrations of trihalomethanes vary considerably from region to region. For example, average THM levels ranged from 15.8–87.2 µg/L in Hong Kong, 18.8–39.0 µg/L in Jiangsu Province, China, 68–99 µg/L in Rajasthan, India, 11.9 µg/L (3.7–20.0 µg/L) in Toronto, Canada, and 1.7–9.4 µg/L in Dhahran, Saudi Arabia (Parveen and Goel, 2023).

Haloacetic acids (HAAs) are also widespread, with concentrations in treated waters often ranging between 10 and 50 µg/L. Goslan et al. (2009) surveyed seven water treatment works in Scotland and observed large differences in HAA9 levels, from 11 to 134 µg/L, with the highest values at upland reservoir sites where organic removal was less effective. The study showed that chlorination produced higher HAA concentrations (median 44 µg/L) than chloramination (median 16 µg/L). A subsequent survey of 12 UK treatment works in 2008 reported seasonal variation, with HAA levels between 0.8 and 23.5 µg/L in winter and 2.7 to 53.8 µg/L in summer (Parsons and Goslan, 2011).

Nitrosamines, particularly N-nitrosodimethylamine (NDMA), typically occur at much lower concentrations, usually in the nanogram per litre (ng/L) range, with most reported values between 1 and 100 ng/L (Mitch et al., 2003).

In Asia, studies report NDMA and other nitrosamines at $ng \cdot L^{-1}$ levels, with typical averages of about 10–15 $ng \cdot L^{-1}$ and regional hotspots reaching near 25–30 $ng \cdot L^{-1}$ in some Chinese systems (Bei et al., 2016).

In Africa, elevated DBP levels have also been reported. In the Western Cape (South Africa), Marshalle (2018) reported measured chloroform concentrations of 10.120 $\mu g \cdot L^{-1}$ to 11.654 $\mu g \cdot L^{-1}$ in chlorinated finished water samples. In Nigeria (West Africa), a survey of drinking-water treatment plants found trihalomethane concentrations in treated water ranging up to 950 $\mu g \cdot L^{-1}$ in individual samples (Benson et al., 2017).

In Tunisia (North Africa), Hammami (2023) reported total THM (TTHM) concentrations between 46 $\mu g \cdot L^{-1}$ and 123 $\mu g \cdot L^{-1}$ and haloacetic acid (HAA) concentrations between 19 $\mu g \cdot L^{-1}$ and 115 $\mu g \cdot L^{-1}$ in finished tap water from the Bizerte distribution system.

Furthermore, many studies (Achour et al., 2002, Achour et al.2009; Achour and Chabbi, 2014), demonstrated that Algerian surface waters have a high potential to form disinfection by-products (DBPs) when chlorinated, particularly trihalomethanes (THMs) and total organic halogens (TOX). Laboratory chlorination tests on several reservoirs showed THM formation potentials in the range of a few tens to just over 100 $\mu g \cdot L^{-1}$, while TOX formation potentials reached several hundred up to nearly 1000 µg $Cl^{-} \cdot L^{-1}$. These values were closely associated with chlorine demand and the presence of humic precursors, especially in reservoirs with high organic matter content such as Beni Haroun and Mexa (Achour et al., 2009). The study by Benhamimed (2017) also determined a

strong presence and seasonal variation of THMs in tap water in the province of Mostaganem (Western Algeria).

Among inorganic DBPs, bromate is a key by-product of ozonation in bromide-containing waters, and its concentration is regulated by the World Health Organization (WHO, 2017) at a guideline value of 10 µg/L.

In systems using chlorine dioxide, elevated levels of chlorite and chlorate can be detected, in some cases reaching several hundred µg/L when operational conditions are not well optimized. In Cremona's water network (Italy), chlorine dioxide showed rapid decay, chlorite occasionally exceeded 700 µg/L in distal zones, chlorate remained below 200 µg/L (Sorlini et al., 2016).

HEALTH IMPACTS OF DISINFECTION BY-PRODUCTS

Disinfection by-products (DBPs) are chemicals formed when oxidants (e.g. chlorine, chloramines, ozone, permanganate, …) react with natural organic matter (NOM), halide ions, nitrogenous precursors, or other constituents in water. Over 600–700 different DBPs have been identified, but only a fraction have been thoroughly studied for toxicity. Many regulated DBPs (such as trihalomethanes, haloacetic acids) and numerous unregulated ones (haloacetonitriles, halonitromethanes, halobenzoquinones, etc.) have been shown in experimental and epidemiological studies to exert cytotoxic, genotoxic, carcinogenic, developmental, and reproductive harm.

Toxicological profile of major DBPs in drinking water

Trihalomethanes (THM)

THMs, including chloroform, bromodichloromethane, dibromochloromethane, and bromoform, are the most studied DBPs. Chronic exposure is consistently associated with an increased risk of bladder cancer and possibly colorectal cancer (Li and Mitch, 2018; Helte et al., 2025). Animal studies also demonstrate liver and kidney toxicity. Some epidemiological studies suggest associations with low birth weight and adverse pregnancy outcomes, although results remain inconsistent (Villanueva et al., 2015; Graves et al., 2001). Toxicity mainly involves oxidative stress and genotoxic mechanisms, with inhalation and dermal exposure contributing due to THM volatility.

Haloacetic acids (HAAs)

HAAs, particularly HAA5, have shown liver carcinogenicity in rodents, especially dichloroacetic and trichloroacetic acids (OEHHA, 2022; Li and Mitch, 2018). They are also linked to developmental toxicity in animal studies, although human data remain limited and inconsistent (Villanueva et al., 2015). The liver is the primary target organ, and mechanisms include mitochondrial dysfunction and direct genotoxicity.

Nitrogenous DBPs (N-DBPs)

Nitrogenous DBPs such as NDMA and haloacetonitriles are generally more toxic than THMs and HAAs, even at ng/L concentrations (Bond et al., 2012; Shah and Mitch, 2012). NDMA is a potent liver carcinogen in animals and a probable human carcinogen (WHO, 2008). Other organohalogenated DBPs also show strong cytotoxicity and genotoxicity, with evidence of multi-organ toxicity in animal studies (Li and Mitch, 2018; Kalita et al., 2024).

Other DBPs

Inorganic DBPs like bromate, chlorite, chlorate, and perchlorate also present health risks. Bromate is a probable human carcinogen (EPA, 2001; OEHHA, 2009), while chlorite and chlorate are linked to hematological and neurodevelopmental effects (WHO, 2017). Perchlorate disrupts thyroid function and may affect fetal and infant neurodevelopment (WHO, 2017; Hao and Zhang, 2025).

Drinking water guidelines for DBPs

Drinking water guidelines for disinfection byproducts (DBPs) vary across the world, reflecting differences in regulatory approaches, available technologies, and health risk assessments.

The World Health Organization (WHO) provides guideline values for commonly studied DBPs such as trihalomethanes (THMs) and haloacetic acids (HAAs), which many countries use as a reference when establishing their own standards.

Table 2 summarizes regulatory values for common disinfection by-products (THMs, HAA5, bromate, and chlorite/chlorate). The abbreviations of the DBPs appearing in Table 2 are used as follows:

TTHM: Total Trihalomethanes ($CHCl_3$: Chloroform; $CHBr_3$: Bromoform; $CHCl_2Br$: Bromodichloromethane; $CHClBr_2$: Dibromochloromethane).

HAA5: sum of 5 haloacetic acids (MCAA: Monochloroacetic acid; DCAA; Dichloroacretic acid; TCAA: Trichloroacetic acid).

Table 2: Guidelines values for DBPs in drinking water

Organization / Country	THMs (µg/L)	HAAs (µg/L)	Bromate (µg/L)	Chlorite (µg/L)	Chlorate (µg/L)
WHO (2000; 2017)	$CHCl_3$: 300 $CHBr_3$: 100 $CHClBr_2$: 100 $CHCl_2Br$: 60	MCAA: 20 DCAA: 50 TCAA :200	10	700	700
USEPA (2001; 2006;2010)	TTHMs: 80	HAA5 : 60	10	1000	No federal MCL
EU (Directive 2020/2184)	TTHMs: 100	HAA5: 60	10	250 (700 where ClO_2 used)	250 (700 where ClO_2 used)
Canada (Health Canada, 2006;2008; 2025)	TTHMs: 100	HAA5: 80	10	1000	1000
Australia (ADWG, 2021)	TTHMs: 250	MCAA: 150 DCAA: 100 TCAA:100	20	800	Data insufficient to set a guideline
Japan (MHLW, 2015)	TTHMs: 100 $CHCl_3$: 60 $CHBr_3$: 90 $CHClBr_2$: 100 $CHCl_2Br$: 30	MCAA: 20 DCAA: 30 TCAA:30	10	not listed in the MHLW table	600
South Africa (SANS 241)	$CHCl_3$: 300 $CHBr_3$: 100 $CHClBr_2$: 100 $CHCl_2Br$: 60	HAA5: 60	10	700	700
Algeria (JORADP, 2014)	$CHCl_3$: 200 $CHBr_3$: 100 $CHClBr_2$: 100 $CHCl_2Br$: 60	HAA not listed as a group value	10	700	not explicitly listed

OVERVIEW OF ALGERIAN WATER RESOURCES AND THEIR QUALITY

Water is one of Algeria's most critical natural resources, fundamental to domestic, agricultural, and industrial development. However, the country faces significant challenges in managing both the quantity and quality of its water resources. The

geographical and climatic conditions of Algeria result in an uneven distribution of water, with limited and irregular rainfall intensifying the scarcity.

Over recent decades, the demand for potable water has increased substantially, compelling the country to mobilize both groundwater and surface water reserves. The management of these resources is central to Algeria's environmental and public health policies, given the persistent shortage and frequent drought episodes.

Water resources in Algeria

In Algeria, drinking water is primarily derived from two main sources: groundwater and surface water. In the southern regions, where the Sahara dominates, groundwater remains the only viable source of drinking water. Nevertheless, studies have shown that these waters often exhibit high concentrations of dissolved minerals, frequently exceeding the limits recommended by the World Health Organization and Algerian Standards. The presence of excess minerals such as fluoride, chloride, and sulfates poses long-term health risks and complicates water treatment processes (Achour and Youcef, 2014; Bouchemal and Achour, 2015).

In contrast, the northern part of Algeria relies increasingly on surface water stored in large reservoirs and dams. These waters are used not only for drinking but also for irrigation and industrial purposes. Despite their growing importance, surface waters are generally of poor quality and often contain significant levels of organic matter (Achour et al., 2009; Achour, 2015; Achour et al., 2019). As a result, ensuring the safety of these water sources requires extensive monitoring and treatment.

Microbiological contamination of water

In Algeria, the deterioration of water quality is exacerbated by the inadequate treatment of domestic and industrial effluents. As of 2024, the country operated only 232 wastewater treatment plants (Mechti, 2024), which is insufficient for the scale of pollution. Consequently, waterborne diseases continue to pose serious public health risks. In 2024, the incidence rate of waterborne diseases increased, rising from 23.64 to 41.67 cases per 100,000 inhabitants (INSP, 2024).

The detection of Escherichia coli (E. coli) in surface waters is a direct indication of fecal contamination and the possible presence of pathogenic microorganisms. According to the United States Environmental Protection Agency (USEPA), the concentration of E. coli in water intended for consumption should not exceed 235 colonies per 100 mL. However, samples collected from various dams consistently exceeded this limit, especially during the dry season (Achour et al., 2014; Achour, 2015).
Ouahchia et al. (2015) studied the water from the Boukourdane Dam in Tipaza, Algeria, and found that it did not meet bacteriological quality standards due to the presence of sulfite-reducing anaerobic spores. However, the water from the Sidi-Amar treatment plant, which uses water from the same dam, as well as from the Tipaza reservoirs, met

the required quality standards. This showed that the water treatment process at Sidi-Amar was effective in removing harmful bacteria and ensuring safe drinking water.
A study conducted on rivers in western Algeria also showed significant amounts of total and fecal coliforms (Guenfoud et al., 2021). This microbiological pollution was explained by the fact that the considered streams serve as outlets for various wastewater discharges from the surrounding urban areas.According to the national guidelines, drinking water must not contain any pathogenic germ and thus no fecal coliform (JORADP, 2014).
These findings confirm that Algerian surface waters are highly susceptible to contamination from untreated urban wastewater, highlighting the necessity for disinfection prior to consumption (Achour and Chabbi, 2014; Achour and Chabbi, 2017).

Surface water quality and physicochemical pollution

In northern Algeria, surface waters are being increasingly exploited for drinking water supply and large-scale irrigation. Nevertheless, their quality remains relatively poor, often containing considerable amounts of organic matter (Achour et al., 2009; Achour, 2015). Furthermore, diverse pollutants originating from urban and industrial wastewater discharges contribute to contamination, sometimes reaching critical levels, especially in river systems.

In Algeria, water quality monitoring is carried out by the National Hydrological Resources Agency (ANRH) and by analytical laboratories belonging to water production companies. Each hydrochemical parameter is evaluated according to the national standards and guidelines in force. In line with the ANRH's mission, monthly sampling is conducted at dam sites to assess water quality parameters.
The parameters analyzed include pH, total dissolved solids (dry residue), dissolved oxygen (DO), nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), phosphate (PO_4^{3-}), biochemical oxygen demand (BOD), and chemical oxygen demand (COD).

Several data from ANRH reveal that most Algerian dams exhibit moderate to high mineralization, with pH values ranging from 6.5 to 8. Organic pollution, expressed through parameters such as BOD_5 and COD, is also prevalent. The high COD/BOD_5 ratios observed indicate that a substantial portion of the organic matter present is non-biodegradable. This pollution originates from multiple sources, including domestic wastewater, industrial discharges, and eutrophication processes. Nitrogen and phosphorus compounds further demonstrate contamination from urban effluents and the excessive use of fertilizers. These combined pollutants degrade the chemical and biological quality of surface water and necessitate rigorous treatment before distribution.
Continuous monitoring from the point of collection to the consumer's tap is essential to maintain compliance with both national and international drinking water standards.

Inorganic and Organic characteristics of some Algerian surface water

The main goal of this phase is to present data related to the inorganic and organic matter found in various surface waters, some of which are potential sources for drinking water treatment plants.

The discussion primarily highlights the research conducted by the LARHYSS laboratory on water samples collected from both northern and southern regions of the country.

The studies (Achour et al., 2008; Achour et al., 2009; Achour et al., 2014; Achour, 2015) assessed the inorganic quality of various dam waters and compared them to WHO and Algerian standards. Overall, water quality ranged from average to poor, with pH near neutral. Southern dams (Foum El Gherza, Fontaine des Gazelles) showed high mineralization, hardness (130–150°F), and conductivity (>1000 µS/cm), likely due to geology. Northern dams were mostly semi-hard with lower conductivities (210–640 µS/cm), except Beni Haroun, which had high pollution levels (nitrates, ammoniacal nitrogen, phosphates). Beni Zid had the best mineral quality. The presence of ammoniacal nitrogen and nitrates suggests contamination from organic decomposition and agriculture, whereas elevated cadmium levels indicate industrial pollution.

Iron and manganese were generally low but higher in southern waters. Bromide levels varied: some high southern levels were geochemical, while coastal Skikda levels (0.19–0.48 mg/L) likely resulted from marine intrusion. Turbidity, especially in northern dams, is mainly of organic origin, affecting water treatment requirements.

As for organic matter, Fig. 2 summarizes the concentration levels of key organic parameters observed in several Algerian dam waters. Studies (Achour et al., 2009; Achour, 2015; Harrat and Achour, 2016) indicate that raw waters show considerable organic pollution, with significant levels of total organic carbon (TOC), humic substances, and UV absorbance. UV optical density measurements suggest that a large portion of this organic matter is associated with humic substances, which are estimated to constitute 40–80% of the dissolved organic carbon (DOC) in these waters (Achour and Guergazi, 2002; Achour et al., 2009; Achour et al., 2014). However, the organic matrix is complex and also contains other natural or anthropogenic non-humic compounds.

The SUVA (Specific Ultraviolet Absorbance) parameter, calculated as DOC divided by UV absorbance at 254 nm (USEPA, 1999), indicates that aromatic organic compounds form a substantial fraction of the total organic load. Higher concentrations of DOC, humic substances, and SUVA are typically observed during the rainy season, largely due to land-use practices that cause runoff of soils rich in humic and non-humic substances into the water. These organic substances can react during disinfection, consuming chlorine and potentially forming toxic organohalogen by-products. Overall, Algerian dam waters are heavily loaded with oxidizable organic matter, which may originate from both natural sources and exogenous pollution such as urban, industrial, and agricultural activities.

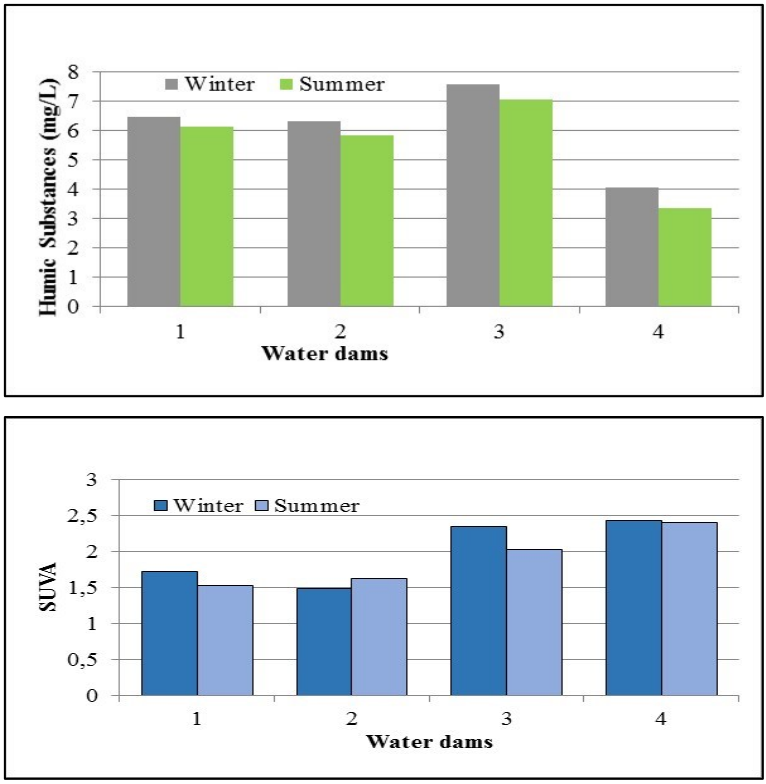


Figure 2: Organic parameters (humic substances, SUVA) of the tested dam waters (Achour, 2015). (1) Keddara; (2) Beni Haroun; (3) Aïn Zada; (4) Foum El Gherza

ORGANIC MATTER REACTIVITY IN ALGERIAN SURFACE WATERS

The studies presented evaluate the impact of chlorination from the perspective of chlorine consumption and the formation of organohalogen compounds as by-products of this chlorination (Achour and Moussaoui, 1993; Achour and Guergazi, 2002; Achour et al, 2009; Achour et al, 2014). Laboratory chlorination tests are carried out on different surface waters (water from dams and rivers) for which different global and organic parameters are determined.
Reaction parameters could be controlled such as the chlorination rate and contact time. The quality of this water is often linked to its reactivity with respect to chlorine.

Organic matter reactivity and chlorine consumption in Algerian surface waters

Early work by Achour and Moussaoui (1993) was the first to demonstrate that Algerian surface waters, especially those from large northern reservoirs, contain substantial

concentrations of humic organic matter capable of consuming large amounts of chlorine. Their study showed that humic substances accounted for 60-90% of total organic carbon, creating a strong intrinsic demand for chlorine immediately after dosing and throughout the contact period. They found that raw waters from the Keddara and Souk-El-Djemâa systems consumed between 7 and 9 $mg \cdot L^{-1}$ of chlorine under typical treatment-plant conditions, highlighting the importance of natural organic matter (NOM) as a dominant reactive constituent.

In this study, raw water samples taken at three different stages of the year concern:

- The Keddara Dam supplies the Boudouaou drinking water treatment plant.
- The reservoir on the Oued Djemaa supplies the Souk-El-Djemâa station.
- Oued Sebaou feeds the Sebaou River through infiltration into the Sebaou alluvial aquifer.

In raw water, the organic load was characterized by total organic carbon (TOC), UV absorbance measured at a wavelength of 254 nm, and the concentration of humic substances (Table 3). Chlorination of these waters, at a dose of 20 mg/L and a contact time of 72 hours, allowed for the determination of the $PCCl_2$ (chlorine consumption potential) .

Table 3: Characteristics and chlorine consumption of surface water (Based on Achour and Moussaoui, 1993)

Water sample	Keddara dam			Souk El Djemaa reservoir			Oued Sebaou	
	April	June	November	April	June	November	April	June
pH	7.6	7.4	7.5	7.7	7.5	7.4	8	8.1
TOC (mg C/L)	5	-	5.1	5.3	-	5.6	16.7	18.2
SH (mg/L)	5.8	6.7	6.8	5.7	6.4	6.3	11.6	12.3
OD λ =254 nm	0.19	0.22	0.23	0.185	0.158	0.2	0.63	0.88
$PCCl_2$ (mg/L)	7.1	8.2	7.8	9.3	7.8	8.3	18.2	15.7

This early dataset firmly established the relationship between humic abundance and chlorine consumption in Algerian waters.

The results presented in this table show that after 72 hours, chlorination can induce a high chlorine demand, part of which becomes unavailable for the desired disinfectant effect.

The study conducted by Achour and Guergazi (2002) sought to deepen the understanding of how total mineralization and specific mineral elements influence the chlorination of organic substances in surface waters. Algerian natural waters, particularly those in the south, are known for their high mineral content, with a dominance of chlorides and sulfates, as well as excessive hardness (Bouchahm and Achour, 2004. Achour et al, 2008).

Given this, it is anticipated that the behavior of chlorine in such mineralized waters would differ notably from its behavior in fresh water.

This work presents the chlorine demand of surface waters from various Algerian dams: Ain Zada and Souk El Djemaa in the north, and Foum El Gherza and Fontaine des Gazelles in the south. The northern dams of the country (Souk el Djemaa and Ain Zada) show chlorine demands of 9.3 and 10.5 mg chlorine/L, respectively, whereas chlorination of southern waters (Foum el Gherza and Fontaine des Gazelles) results in 5.9 and 7.4 mg chlorine/L. The results reveal that chlorine demands are considerable after 72 hours of contact, and the differences observed among the various waters can be linked to their physicochemical properties, particularly the nature and levels of both organic and inorganic constituents. Waters with high levels of humic substances, which constitute the predominant fraction of total organic carbon (TOC), exhibit the highest chlorine consumption potential.

The observed differences in reactivity between the waters can also be linked to the presence of certain mineral elements that influence chlorine consumption. Reducing agents like ammonia, bromides, iron, and manganese can engage in competing reactions with chlorine, affecting its availability to react with organic matter (Achour and Guergazi, 2002; Achour, 2012). Additionally, the highly mineralized waters of southern Algeria seem to follow a complex reaction pattern, where high chloride and sulfate content may result in different chlorine demands compared to less mineralized waters.

A similar conclusion is drawn from studies on the chlorination of dam waters in Eastern Algeria (Achour et al., 2009). Table 4 summarizes the results of the determination of $PCCl_2$, which reflects the maximum reactivity of water to chlorine under extreme conditions (24 hours contact time and a chlorine dose of 20 mg/L).

The chlorine consumption values for the different dams range from 5.80 to 16.22 mg Cl_2/L, with the highest chlorine demand observed in the Beni Haroun dam water, which contains high concentrations of chlorine-reactive compounds such as organic matter, ammonia, and bromides. Moreover, waters with high humic organic loads, such as those from the Chefia and Mexa dams, exhibit greater chlorine demand compared to those with lower humic content, like Foum El Gherza, Fontaine des Gazelles, and Beni Zid. The waters of Zardezas and Ain Dalia have relatively low levels of humic organic matter (18 to 28%), but their high chlorine consumption is likely due to the presence of non-humic organic compounds that are particularly reactive with chlorine.

The change in UV absorbance after 24 hours, a characteristic of aromaticity, indicates that a fraction of the organic matter present may have been degraded into aliphatic structures, including THMs such as chloroform.

Table 4: Chlorine consumption of dam waters in Eastern Algeria (Achour et al., 2009; Harrat and Achour, 2010)

Water dams	$PCCl_2$ ($mgCl_2/L$)	UV decrease (%)
Zardezas	12.30	22.58
Beni Zid	7.58	35.36
Ain Zada	9.55	32.55
Ain Dalia	9.35	21.31
Hammam Debagh	10.46	60.33
Hammam Ghrouz	9.90	24.39
Chefia	10.32	20.67
Mexa	12.48	22.44
Fontaine des gazelles	6.00	50.00
Foum El Gherza	5.80	71.83
Beni Haroun	16.22	30.88

Mechanistic interpretation: why organic matter consumes chlorine in Algerian waters

Chlorine ($HOCl$ / OCl^-) reacts with organic compounds through a combination of electrophilic halogenation of aromatic moieties, oxidation of phenolic and amino functional groups, and cleavage of conjugated structures leading to smaller, halogenated molecules. Humic substances—complex, heterogeneous macromolecules enriched in phenolic and aromatic structures—provide numerous reactive sites per unit carbon and therefore exert a disproportionately large chlorine demand relative to their mass. This mechanistic view is consistent with spectroscopic proxies: higher UV254 absorbance (indicative of aromaticity) correlates strongly with greater chlorine consumption across sampled surface waters.

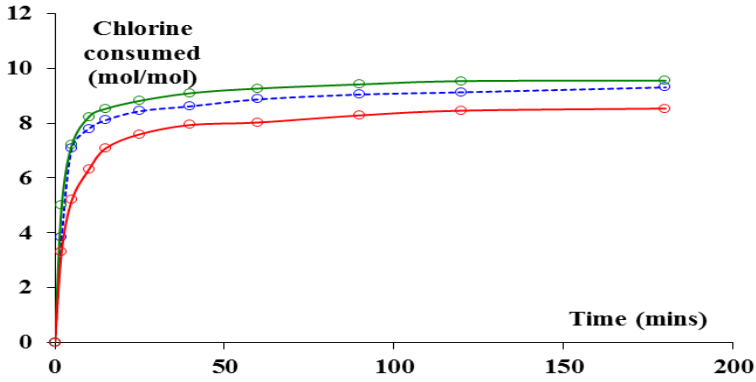
Studies on chlorination often focus on model compounds, such as humic substances, phenols, and carboxylic organic acids, to understand the chemical reactions that occur during chlorination of surface water. These studies provide crucial insights into the complex interactions between chlorine and organic substances in water, helping to optimize water treatment processes and minimize the formation of harmful DBPs.

Research has focused on studying the behavior of aromatic organic acids, substituted with carboxyl and hydroxyl groups, during a chlorination treatment process. The experiments were carried out using chlorination tests with diluted sodium hypochlorite on solutions of phthalic acid, gallic acid, phenol, resorcinol and phloroglucinol dissolved in distilled water (Achour and Guergazi, 2002; Achour et al., 2016; Khelili et Achour, 2017). The chlorine consumption values after 1 hour and especially after 24 hours (chlorine consumption potentials) highlighted their significant reactivity in the presence of chlorine and revealed differences in reactivity based on their chemical structure.

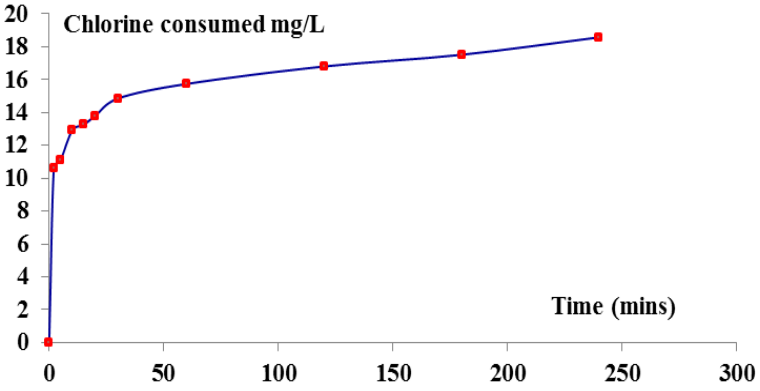
Some data and experiments (Achour et al, 2016; Achour et al.2018; Achour et al; 2019) indicate a two-stage reaction behavior: an initial fast phase (minutes) responsible for most of the chlorine uptake—likely electrophilic substitution and rapid oxidation of phenolic moieties, followed by a slower phase (hours to days) corresponding to deeper oxidation, fragmentation and secondary halogenation.
The evolution of chlorine consumption over time, along with changes in UV absorbance, showed two distinct phases: a rapid phase followed by a slower phase, typical of most organic acids. The differences in reactivity between compounds can be correlated to the nature and position of the substituents on the aromatic ring.

The pH plays a crucial role during the chlorination of humic substances, aromatic compounds, and, more broadly, natural organic matter in surface waters. It strongly influences chlorine speciation, reaction rates, and the pathways leading to disinfection by-products. At lower pH, hypochlorous acid (HOCl) dominates and reacts more rapidly with aromatic moieties, enhancing both chlorine demand and the formation of chlorinated intermediates. At higher pH, the less reactive hypochlorite ion (OCl^-) slows these reactions and can shift product distribution. As a result, pH not only governs the efficiency of chlorination but also shapes the transformation of complex organic matter and the nature of by-products formed during drinking-water treatment.

This is consistent with observed rapid increases in the first 5 minutes for phenol and humic substrates reported in their reactivity study (Fig. 3).



(a) phenol:(o) pH = 4; (o) pH = 7; (o) pH = 9.



(b) Humic substances (10mg/L); pH=7

Figure 3: Kinetics of chlorine consumption by phenol (a) and humic substances (b).

Reaction parameters such as pH and contact time were found to significantly affect the interaction between chlorine and organic compounds (Achour, 2012; Achour et al., 2016; Khelili and Achour, 2017). It is crucial to understand that as the pH rises from 4 to 9, free chlorine shifts from HClO to ClO^-. As a result, chlorination mechanisms are affected not only by the speciation of chlorine but also by the structure of the organic compound, which can change depending on the pH (protonated, neutral, or negatively charged).

These mechanisms involve slow, rate-limiting steps at basic pH for phenols and at acidic or neutral pH for other compounds, potentially leading to the formation of different chlorination products based on the pH.

Maintaining proper pH levels in water systems requires careful control. Both very high and very low pH levels can pose serious risks, impacting the safety and quality of drinking water.

Impact of Water Mineralization and Salinity on Chlorine–Organic Matter Interactions

The inorganic composition of water plays a significant role in chlorination processes and strongly influences chlorine–organic matter reactions. Inorganic ions such as bicarbonates, chlorides, bromides, and metals can modify chlorine speciation, buffer pH, or participate in competing reactions. For example, bicarbonate alkalinity can stabilize pH and slow chlorine decay, while bromide can be oxidized to bromine species that react differently—and often more rapidly—with natural organic matter. Certain metals or reduced inorganic species (such as iron II or sulphides) can also consume chlorine directly, reducing the disinfectant available for reactions with organic matter. Overall, the mineral matrix of surface waters shapes both the kinetics and pathways of chlorination, influencing disinfectant demand as well as the nature and quantity of disinfection by-products formed.

Two additional mechanistic modifiers observed in the Algerian data are especially important:

- **- Ionic matrix effects:** High ionic strength, and the presence of major anions such as Cl^- and SO_4^{2-}, decreases the apparent activity of hypochlorous acid and alters reaction pathways, often reducing measured chlorine consumption potentials relative to distilled-water experiments. This was reported in the reactivity study where chloride and sulfate reduced the $PCCl_2$ values, ,likely by decreasing the activity of the chlorinating species (Achour and Guergazi, 2002; Achour et al., 2016).
- **- Competing inorganic reactants:** Ammonia (NH_4^+), bromide (Br^-), and nitrites (NO_2^- compete for free chlorine (Achour, 2012; Hellal and Achour, 2016; Achour et al., 2018). High ammonia leads to chloramine formation and apparent reduction in free-chlorine available to oxidize organic matter, while bromide oxidation produces HOBr, which favors brominated by-products and can change the chlorine demand dynamics.

These competitive reactions were shown experimentally in many studies (Achour and Guergazi; 2002; Afoufou and Achour, 2004; Achour et al., 2016; Hellal and Achour, 2016; Achour et al., 2018; Achour, 2022). Organic surrogates (phenols, amino acids, humic substances) showed markedly different reactivity when dissolved in highly mineralized Algerian water compared to demineralized water, demonstrating that Algerian ionic matrices amplify chlorine reactions. The results show that the tested organic compounds remain very reactive towards chlorine whatever the mineralization of their dilution medium.

In the experiments conducted by Hellal and Achour (2008) and Achour (2015), humic substances and the aromatic amino acid phenylalanine were selected for testing (Table 5). The results indicated that chlorine consumption, and thus the reactivity of the two organic compounds, was significantly higher in mineralized water compared to distilled water.

Tests on solutions of humic substances in different mineralized waters (Ifri and Drauh) showed that the presence of ammoniacal nitrogen shifted the chlorination breakpoint curve, indicating higher chlorine demand (Fig. 4). The breakpoint occurred at Cl/N ratios above the theoretical value of 7.6, especially in waters with higher mineral content. Ifri water, in particular, showed a more clearly defined breakpoint, suggesting better chloramine degradation compared to Drauh water.

Table 5: Chlorine consumption potentials of the tested organic compounds (m = 2; t = 24 h)

Organic compound	Water dilution	$PCCl_2$ (mg Cl_2/mg organic)
Humic substances	Distilled water (pH =7)	1.125
	Sidi Khelil (borehole)	1.630
	Ain Dalia (Dam)	1.920
Phenylalanine	Distlled water (pH=7)	0.880
	Drauh (boehole)	0.893
	El Hadjeb (borehole)	0.921
	Ain Dalia (dam)	0.946

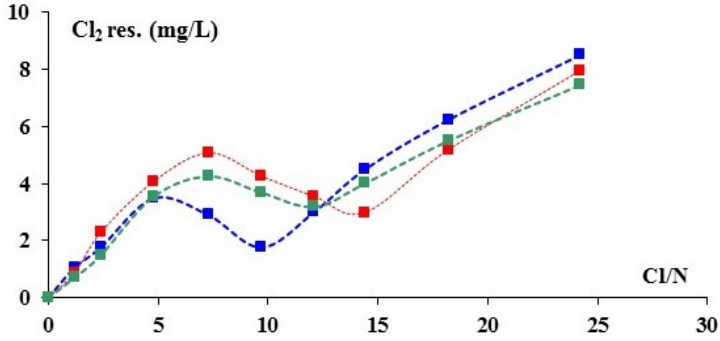


Figure 4: Effect of Cl/N Ratio on Residual Chlorine in SH Solutions in different Waters: (■) Distilled water; (■) Ifri water ; (■) Drauh water. SH: 10 mg/L; NH_4^+: 2 mg/L; t = 2 h

FORMATION AND OCCURRENCE OF DISINFECTION BY-PRODUCTS (DBPS) IN ALGERIAN SURFACE WATERS

Studies were conducted on Algerian surface waters, primarily reservoir waters from diverse climatic regions. They show that chlorination leads to the formation of significant amounts of trihalomethanes (THMs) and total organic halogens (TOX). The reactivity of these waters toward chlorine is strongly controlled by the quantity and quality of natural organic matter (NOM), particularly humic substances.

General characteristics of DBP formation in Algerian surface waters

Laboratory chlorination experiments (Achour et al., 2009; Achour et al., 2014) performed on raw waters from multiple Algerian reservoirs reveal a consistently high potential for the formation of halogenated disinfection by-products (DBPs).
Under standardized test conditions (20 mg·L^{-1} Cl_2; 24-72 h contact), the waters generate substantial quantities of both volatile DBPs, represented primarily by trihalomethanes (THMs), and non-volatile halogenated compounds, quantified through total organic halogens (TOX) (Table 6).

The values obtained represent the maximum THM concentrations likely to form during chlorination of surface waters. These levels remain below the recommended guideline values for chloroform, and for brominated derivatives (JORADP, 2014; WHO, 2017). However, THMs have been classified as potentially carcinogenic based on animal studies and epidemiological evidence in humans (WHO, 2017; Health Canada, 2006). Therefore, regulations recommend reducing THM concentrations to the lowest achievable level without compromising the effectiveness of water disinfection.

Table 6: Chlorine Reactivity Potentials of Reservoir Waters from Eastern Algeria.

Water Dam	$PCCl_2$ ($mgCl_2/L$)	THM (µg/L)	TOX (µg Cl^-/L)
Zardezas	12.30	65	726
Beni Zid	7.58	67	493
Ain Zada	9.55	72	721
Ain Dalia	9.35	46	489
Hammam Debagh	10.46	62	860
Hammam Ghrouz	9.90	81	608
Chefia	10.32	93	792
Mexa	1248	112	822
Fontaine des gazelles	6.00	45	450
Foum El Gherza	5.80	39	471
Beni Haroun	16.22	78	985

TOX measurements in the study by Achour et al. (2009) show high values, indicating the formation of chlorinated or brominated substitution products, which generally follow the same trend as chlorine demand. Among the potential TOX precursors, humic substances clearly play a major role. Nevertheless, other organic compounds commonly found in natural waters, such as algae and amino acids, may also produce numerous chlorination by-products.

TOX values typically range between 400 and 1000 µg $Cl \cdot L^{-1}$, indicating extensive incorporation of halogens into organic matrix components. Because THMs only represent the volatile fraction of this pool, their concentrations (often >100 µg $\cdot L^{-1}$) account for only 5–20% of the total halogenation, demonstrating that the majority of DBPs formed in these waters belong to non-volatile classes such as haloacetic acids, haloacetonitriles, haloketones, and substitution products.

Alongside the assessment of chlorine demand, another study (Achour and Moussaoui, 1993) monitored the formation of chlorination by-products by analyzing THMs ($CHCl_3$, $CHCl_2Br$, $CHClBr_2$) using chromatography and measuring the total organic halogens (TOX).Table 7 summarizes the THM and TOX levels for three surface waters (Keddara dam, reservoir of Souk El Djemaa and River or Oued Sebaou).

The findings presented in this table suggest that after 72 hours, chlorinating surface waters can result in significant concentrations of both THMs and TOX. Based on the humic substance content, it is likely that these compounds are primarily derived from them. However, for the Oued Sebaou waters, where SH represent only about 30% of the TOC it is also possible that some of the organohalogenated compounds originate from industrial or agricultural pollution (Achour and Moussaoui, 1993; Achour, 2012).

This distribution confirms that Algerian surface waters contain organic matter with high intrinsic reactivity, capable of extensive electrophilic halogenation during chlorination. The THM and TOX levels determined in all Algerian studies represent the maximum possible concentrations of organohalogenated compounds that can form during the

chlorination of these waters. Nonetheless, these findings are consistent with most of the published data on the chlorination of surface waters from various regions around the world (Garcia and Moreno, 2006; Golea et al., 2017).

Table 7: Organohalogen formation potential in Algerian surface waters

Surface water	Keddara	Souk El Djemaâ	Oued Sebaou
$PCCl_2$ ($mgCl_2/l$)	7.1	9.3	18.2
$CHCl_3$ (µg/l)	169	158	246
$CHCl_2Br$ (µg/l)	32	23	55
$CHClBr_2$ (µg/l)	07	00	13
TOX ($\mu gCl^-/l$)	963	1113	858
$X\% = 100 \times 3[CHCl_3]/[Cl_2.cons]$	4.2	3	2.4
$Z\% = 100 \times [\ TOX/35.5\ ]/[Cl_{2.cons.}]$	27.2	23.9	9.4

Table 7 further illustrates the distribution of chlorine consumption, showing that X% of the chlorine is converted into chloroform and Z% into TOX. Based on these results, we can also observe that among the THMs, chloroform is the predominant compound. However, it represents only one of the possible chlorination products formed from algerian tested waters. This is confirmed by the calculation of the parameter X%, which shows that only about 2 to 4% of the chlorine consumed is actually converted into chloroform. The values of X% and Z% indicate that only a small amount of the introduced chlorine is used in substitution reactions.

This demonstrates that chlorine is not only consumed by organic matter to form organohalogenated compounds but also reacts with inorganic reductants, such as ammonia.

In aqueous environments containing ammoniacal nitrogen, organic matter, and chlorine, competitive reactions occur between chlorine and ammonia, and between chlorine and organic matter. The formation of chloramines (from chlorine–ammonia reactions) takes place alongside the formation of organohalogenated compounds (from chlorine–organic matter reactions), particularly trihalomethanes (THMs). Fig. 5 highlights the formation of trihalomethanes in competition with the formation and destruction of chloramines. The test performed on water from the Keddara reservoir (Achour, 2012).

The results of Fig. 5 show that significant amounts of THMs form even at chlorine doses below the break-point. This is attributed to the presence of reactive compounds in the water that compete with chloramine formation and degradation. These compounds are mainly humic substances, due to their aromatic, especially phenolic structures.

Since drinking water disinfection is always carried out beyond the break-point, THM formation will inevitably occur in the presence of free chlorine and an organic matrix whose reactivity competes with that of ammoniacal nitrogen.

THM levels may increase considerably when excessive amounts of free chlorine are applied (over-chlorination) and when the treatment steps preceding disinfection are not properly optimized to remove the organic precursors of organohalogenated compounds.

This also calls into question the practice of pre-chlorination for surface waters rich in humic substances.

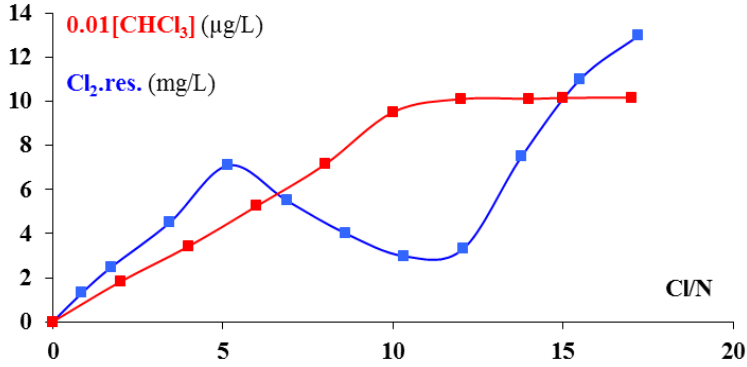


Figure 5: Influence of the Chlorination Rate on the Raw Water from the Keddara Reservoir (Achour, 2012)

Seasonal influence on DBP formation

The seasonal data reveal that DBP formation is strongly temperature-dependent. As illustrated in Fig.6 and table 8, THM and TOX formation potentials increase markedly from winter to summer across all studied reservoirs.

This seasonal amplification reflects the "Arrhenius-driven acceleration" of chlorination kinetics, in which higher temperatures increase the reaction rate of HOCl/OCl^- with dissolved organic matter (DOM). Temperature-accelerated halogenationis a well-established phenomenon in chlorinated natural waters, referring to the increase in the rate at which organic matter reacts with chlorine (or other halogens) as temperature rises.

Elevated temperatures enhance molecular mobility, promote faster reaction kinetics, and increase the formation of halogenated by-products such as trihalomethanes (THMs) and other organohalogenated compounds (Alver et al., 2025).

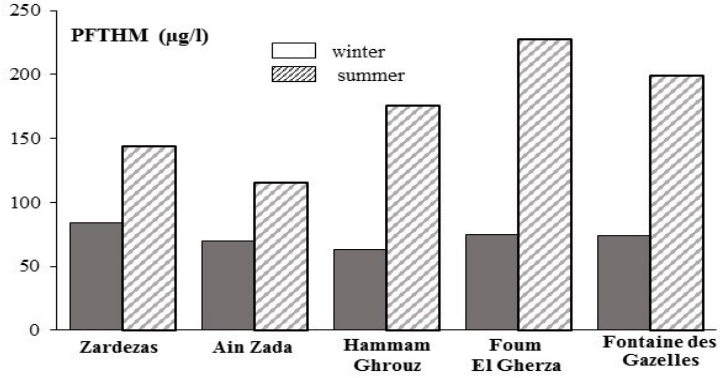


Figure 6: Seasonal variation of THM in some Algerian water dams (Achour, 2005)

Table 8: Effect of temperature on TOX formation in Algerian water dams (Achour, 2012; Achour, 2015)

TOX (µgCl⁻/L)	Water dam	Ain Dalia water	Hammam Debagh water	Keddara water	Souk El Djemma water	Foum El Gherza water
	Winter	489	860	1007	1135	645
	Summer	534	901	1050	1220	853

In the Algerian context, the region experiences strong seasonal thermal variations, with surface water temperatures rising sharply during the summer months. These high temperatures significantly accelerate halogenation reactions, leading to higher levels of disinfection by-products compared to cooler climates.

As a result, temperature becomes a critical factor in managing chlorination efficiency and controlling the formation of potentially harmful organohalogenated compounds in Algerian surface waters. The effect is most pronounced in southern basins of Algeria, where summer water temperatures often exceed 25–30°C.

Influence of bromides on THM speciation in chlorinated Algerian waters

Bromides play a central role in shaping the distribution of trihalomethanes (THMs) formed during chlorination in Algeria's diverse water sources.

In highly mineralized waters of the northern Sahara, such as those of Drauh, Oued Biskra, and Foum El Gherza dam bromide concentrations frequently exceed 1 mg/L and reach up to 2 mg/L (Achour, 2015).

Under these conditions, bromides are rapidly oxidized to hypobromous acid, a more powerful halogenating agent than hypochlorous acid. Therefore, the speciation of THMs shifts markedly: instead of chloroform dominating as in most freshwater systems,

dibromochloromethane and even bromoform can emerge as significant, sometimes major, THM species (Table 9).

This trend is consistent with documented observations that even moderate salinity (equivalent to only ~3% of seawater) combined with bromide levels near 2 mg/L can cause brominated THMs to become predominant in chlorinated Algerian waters (Achour, 2012).

Table 9: Concentration of THMs and chlorine consumption ($PCCl_2$) in chlorinated surface water samples (Based on Achour, 2012; Achour, 2015)

Water dam	Aïn Zada	Beni Zid	Zardezas	Foum El Gherza
$CHCl_3$ (µg/L)	97	72	80	51
$CHCl_2Br$ (µg/L)	09	13	13	19
$CHClBr_2$ (µg/L)	03	7	8	10
$CHBr_3$ (µg/L)	<1	<1	<1	7
$PCCl_2$ (mg/L)	10.2	7.6	7.5	6.2

For all the waters tested, chloroform was the predominant THM formed. However, the proportion of brominated THMs—particularly bromoform—increased significantly with the initial bromide content of the water, as observed in southern water (Foum El Gherza) and in coastal reservoirs such as Zardezas and Beni Zid.

Laboratory analyses (Achour, 2005; Achour et al., 2014; Achour and Chabbi, 2014) confirm this progressive shift in THM repartition. In chlorinated raw waters from Ain Beni Haroun and Keddara, chloroform remains the principal THM, yet measurable amounts of bromodichloromethane and dibromochloromethane appear systematically. Bromoform can also be detected when bromide levels are sufficiently elevated, particularly in Biskra waters.

This illustrates a continuum of THM profiles across Algeria: low-bromide northern waters yield predominantly chlorinated THMs, while bromide-rich southern and mineralized waters generate more highly brominated species.

Coastal and near-coastal water sources subject to marine influence also show a tendency toward increased formation of brominated species, albeit at lower levels than those observed in the Sahara. Even relatively modest bromide concentrations in such waters are sufficient to shift THM distribution away from pure chloroform and toward mixed chlorine–bromine THMs when chlorination is applied.

Altogether, Algeria presents a marked geographical gradient in THM repartition driven largely by bromide availability: northern, less mineralized waters produce mainly chloroform; central and coastal waters show mixed species; and southern mineralized basins with elevated bromides tend to produce higher proportions of brominated and potentially more toxic THMs. This pattern highlights the importance of accounting for bromide levels—and not only organic precursors—when predicting DBP formation and assessing risks associated with chlorination in Algerian drinking water systems.

POTENTIAL HEALTH IMPACTS OF DBPS ON PUBLIC HEALTH IN ALGERIA

The occurrence of disinfection by-products (DBPs) in drinking water is increasingly acknowledged as a potential determinant of adverse health outcomes due to their established mutagenic, carcinogenic, and systemic effects (WHO, 2017; Li and Mitch, 2018; Kalita et al., 2024).

In Algeria, where chlorination constitutes the primary disinfection strategy, the formation profiles and exposure patterns of DBPs may give rise to health risks that remain insufficiently characterized from a toxicological and epidemiological standpoint. Beyond their broad spectrum of toxic effects, several DBP classes, particularly trihalomethanes and haloacetic acids, have been associated in the literature with elevated cancer risk indicators.

Based on the DBP levels previously reported in Algerian drinking water, it is plausible to consider that long-term exposure could contribute to cancer risk, as suggested by international toxicological and epidemiological studies. While a direct causal relationship has not been established in Algeria, the known mutagenic and carcinogenic properties of certain DBP classes, such as trihalomethanes and haloacetic acids, provide a basis for hypothesizing a potential link. This reflection is intended to contextualize the possible public health implications without implying confirmed associations.

Within this framework, the present phase of the work aims to articulate a hypothesis-driven assessment and a concise analytical perspective on the potential causal plausibility between DBP occurrence in Algerian drinking-water systems and the recent upward trends in cancer incidence reported nationally.

A Major Public Health Burden: Cancer in Algeria

Cancer is currently the second leading cause of death in Algeria, after cardiovascular diseases, affecting both men and women (Gralén et al., 2025). This growing burden has prompted strong governmental mobilization. In recent years, the increasing incidence and impact of cancer have been sufficiently substantial to drive national health authorities to prioritize oncology within public health planning, reflecting the scale and persistence of the problem.

As the largest country in Africa and now classified as an upper middle-income country, Algeria has intensified its investments to improve cancer care. The number of radiotherapy centers has increased, dedicated funding mechanisms have been created, and a National Commission for the Prevention and Control of Cancer was established in 2024 to coordinate nationwide oncology policies.

Cancer incidence in Algeria is rising, with five major cancers accounting for ~63% of cases in both men and women. Colorectal cancer (CRC) has increased sharply (3.7% annually), becoming the leading cancer among men since 2017 (Hammouda and Boutekdjiret, 2020), affecting both sexes equally. Prostate and bladder cancers are also

rising across all regions. These trends coincide with demographic and socio-environmental shifts, including dietary westernization, reduced physical activity, urbanization, and industrial pollution.

Regionally, North African cancer incidence is medium (100–150 per 100,000), but northern Algeria approaches Southern European rates while remaining below Western Europe and North America (>300 per 100,000). GLOBOCAN 2022 reported 64,713 new cases and 35,778 deaths, with a 5-year prevalence of 177,718 and an age-standardized incidence of 141.2 per 100,000 (130.6 for men, 152.2 for women).

Analysis of 112,117 cases from the Algiers Cancer Registry (2002–2021) by Bouheraoua et al. (2024) showed annual new cases rising from 4,069 to 7,143, with steadily increasing colorectal, bladder, and stomach cancers, potentially linked to chronic DBP exposure. Regional data from 20 wilaya (2014–2017) indicated 90% population coverage, a crude incidence of 143.3 per 100,000, and an age-standardized rate of 178.0 per 100,000 (Hamdi Cherif et al., 2020).

In 2022, most common cancers in women were breast, colorectal, thyroid, stomach, and cervical; in men, lung, colorectal, prostate, and bladder (GLOBOCAN, 2022). CRC is a growing concern, representing 14% of male and 11% of female cancers, and is the second leading cause of cancer death. Algeria ranks fifth in CRC incidence and mortality among 28 North African, Central, and Western Asian countries (Gralén et al., 2025). Herrag et al. (2024) noted increasing CRC incidence, including among younger adults, suggesting environmental and genetic influences.

Bladder cancer has also risen, with 3,201 new cases in 2020 (5.5% of all cancers) (Bouamra, 2024). Overall, Algeria shows a clear epidemiological shift, emphasizing colorectal, bladder, and prostate cancers as priority targets for prevention and control.

Potential Contribution of DBPs in Algerian Water to Cancer Incidence

While there is a lack of specific epidemiological studies directly linking disinfection by-products (DBPs) in drinking water to cancer in Algeria, the country has seen a troubling rise in cancer incidence over the past few decades, which warrants attention.

Algerian reports and studies do not explicitly examine environmental causes. Nevertheless, the alignment of long-term incidence trends with known DBP-related risk profiles underscores the need for integrated research that connects cancer registries with routine monitoring of drinking water contaminants. Such research would be crucial to determine whether DBPs contribute to the increasing burden of these cancers in Algeria.

The sustained rise of cancer to the position of second leading cause of mortality in Algeria reflects a long-term escalation in both incidence and morbidity, suggesting that the country is undergoing a significant epidemiological transition. The persistence of this mortality ranking over time, affecting both sexes, indicates that the upward trend is not attributable to isolated demographic or behavioral shifts but rather to broad, population-level determinants. This pattern is consistent with multifactorial etiologies in which environmental exposures may interact with established lifestyle and genetic risk factors.

Taken together, data from Algerian studies indicate that, among the cancers exhibiting the most sustained increase over the past two decades, colorectal, bladder, and gastric cancers are particularly prominent. These malignancies are also consistently identified in the scientific literature as potentially influenced by chronic exposure to disinfection by-products (DBPs). The increasing incidence of cancers such as colorectal and bladder cancer in Algeria, coupled with the widespread use of chlorination in water treatment, suggests that DBPs could be contributing to the country's growing cancer burden.

The prominence of bladder cancer within the national cancer profile is notable, given its well-established association with chronic exposure to trihalomethanes (THMs) and related DBPs in chlorinated drinking water systems. Similarly, the significant representation of colorectal cancer aligns with global findings implicating haloacetic acids (HAAs) as potential contributors to gastrointestinal carcinogenesis. These malignancies, which occupy a substantial share of reported cancer cases in Algeria, provide biologically plausible targets for evaluating environmentally mediated carcinogenic pathways.

International research has shown that long-term exposure to certain DBPs may be associated with increased risks of cancer, digestive and urinary tract cancer. In Algeria, where water quality is variable, and chlorination is sometimes intensified to ensure microbiological safety, the potential for elevated DBP formation is plausible and should not be overlooked.

The Algerian context presents several conditions conducive to recurrent DBP formation, including reliance on chlorine-based disinfection, elevated organic loads in raw water sources, and climatic conditions that enhance DBP yields. In environments where such conditions persist, even modest DBP exposures, sustained over many years, may produce detectable population-level effects, particularly in malignancies with established exposure–response relationships. The increase in total cancer burden therefore raises the possibility that DBPs could represent one component of a broader constellation of environmental risk factors influencing cancer trends.

An important consideration is the current lack of systematic monitoring of DBP concentrations and population exposure levels in Algeria. This gap limits the ability to quantify attributable risk and constrains epidemiological interpretationAlthough such data are not yet available for Algeria, the observed cancer patterns, particularly the high prevalence of DBP-sensitive malignancies, support the need for targeted investigation.

Studies have not yet established a causal link between disinfection by-products (DBPs) in Algerian drinking water and cancer. However, DBPs, formed during routine water treatment, may pose a potential environmental risk to public health. International studies indicate that some DBPs have carcinogenic properties, highlighting the importance of systematic monitoring, improved water treatment practices, and targeted epidemiological research in Algeria. Proactive measures could help reduce future cancer risk and improve drinking water safety.

STRATEGIES AND METHODS FOR CONTROLLING FORMATION OF DBPS IN DRINKING WATER

The formation of disinfection by-products (DBPs) during drinking water treatment remains a major challenge for water utilities worldwide. Although disinfection is essential for microbiological safety, the unintended reaction between disinfectants and natural organic matter (NOM) or other precursors can lead to the formation of potentially harmful compounds, including trihalomethanes (THMs), haloacetic acids (HAAs), and emerging DBPs. Effective control strategies must therefore aim to minimize DBP formation while maintaining adequate microbial protection.

Global Strategies for DBP Control and mitigation

To mitigate DBP formation, water treatment facilities can implement several strategies. Internationally, strategies to control DBPs can be grouped into three main approaches:

- precursor removal,
- optimization of disinfection practices, and
- post-formation DBP removal.

Control of disinfection byproducts (DBPs) in drinking water is a complex, type-specific process that requires a thorough understanding of both precursor chemistry and treatment dynamics.

Carbonaceous disinfection by-products (C-DBPs), such as trihalomethanes (THMs), haloacetic acids (HAAs), haloketones, and haloacetaldehydes, are primarily formed when natural organic matter (NOM) reacts with chlorine or other oxidizing disinfectants (Deborde and Gunten, 2008). The most effective strategies to control C-DBPs target the reduction of these organic precursors. Conventional strategies such as precursor removal combined with optimized chlorination conditions remain effective (Singer, 1994; Alver et al., 2025).

For nitrogenous DBPs (N-DBPs), including nitrosamines, halonitromethanes, and haloacetamides, control is more challenging due to their origin from nitrogenous precursors, e.g. dissolved organic nitrogen, amines (USEPA, 2016; Zheng et al., 2018).

Precursor removal by enhanced coagulation and advanced treatment processes

Enhanced coagulation using aluminum or iron salts has been shown to preferentially remove hydrophobic NOM, which is highly reactive with chlorine (USEPA, 1999; Garcia, 2011; Bacha and Achour, 2023). The fraction of NOM that contributes to DBP formation is a blend of humic and fulvic acids, commonly assessed through total organic carbon (TOC), dissolved organic carbon (DOC), and UV absorbance at 254 nm or Specific ultraviolet absorbance (SUVA).

For instance, Rizzo et al. (2005) examined TOC and turbidity removal through enhanced coagulation using alum and ferric chloride without pH adjustment. They found that the 15% TOC reduction required by the USEPA DBP rule could be met with 30–50 mg L^{-1} of coagulant. However, achieving the stricter Italian TTHM limit required over 30% TOC removal, which in turn needed higher doses of about 80 mg L^{-1}, also necessary to meet the <1 NTU turbidity standard. At 80 mg L^{-1}, alum and ferric chloride achieved roughly 33–36% TOC removal and turbidity below one NTU. For even lower turbidity levels (0.1-0.2 NTU) required for pathogen control, additional treatments such as GAC adsorption or sand/microfiltration may be needed to avoid excessive coagulant use.

In trials on South African waters, Pryor and Freese (1998) reported that enhanced coagulation without pH adjustment could achieve up to 60% removal of TOC/COD, up to 40% of THMFP, and between 70% and 90% of COBD, although the removal efficiency varied depending on the characteristics of the water. They highlighted that enhanced coagulation is effective for removing TOC, DOC, BDOC, THM precursors, and colour. However, it is not effective for eliminating micro-pollutants or taste- and odour-causing compounds, which must be considered when selecting the most suitable treatment strategy.

In addition, inorganic coagulants such as ferric chloride and alum generally perform better than polymeric coagulants in enhanced coagulation processes. The optimal coagulant dose is usually between 1.5 and 7 times higher than the dose required for turbidity removal, and therefore must be determined through laboratory, pilot-plant, or full-scale testing. Moreover, high alkalinity can reduce coagulation performance, while lowering the pH with acid to between 5.0 and 5.5 can significantly improve NOM removal.

Combined ozonation and coagulation has also been shown to reduce TOC by 28–38% and UV absorbance by 48-73%, corresponding to a 50–56% decrease in THM formation potential (Dąbrowska, 2020).

By adding aluminium sulfate as a coagulant and bentonite as a flocculation aid, the study conducted by Guesbaya and Achour (2003) examined the impact of the chlorination phase on the treatment of water from Souk El Djemâa and Foum El Gherza, both before and after the coagulation–flocculation process. Table 10 presents the results obtained regarding the evolution of turbidity, organic matter, chlorine demand potential ($PCCl_2$), and THM formation.

Table 10: Effect of chlorination on quality of flocculated water dam of Souk El Djemaa (SED) and Foum El Gherza (FEG)

Parameters	Prechlorination		Prechlorination + Coagulation-flocculation		Coagulation-flocculation + Bentonite + post chlorination	
	SED	FEG	SED	FEG	SED	FEG
Chlorine Demand ($mgCl_2/L$)	9.2	9.4	7.1	6.9	3.8	2.9
$CHCl_3$ (µg/L)	62.0	38.0	54.5	30.8	18.5	12.8

Pre-chlorination generated a significant amount of chloroform, which was only slightly removed after coagulation–flocculation (Achour, 2015). However, when bentonite was used in combination with aluminium sulfate and pre-chlorination was eliminated, the removal of organic matter, particularly humic-type precursors, became much more effective.

Coagulation enhanced with adsorption on bentonitic clay or powdered activated carbon (PAC) is greater effectiveness of humic compounds removal in comparison with coagulation without the addition of coagulant aid (Achour and Bacha, 2014; Harrat and Achour, 2016). The bentonite added to the treated solution acts not only as an adsorbent for organics but also enhances the settleability of flocs formed.As a result, both THM formation and chlorine demand during post-chlorination were considerably reduced.

Adsorption using granular activated carbon (GAC) is another highly effective strategy. However, the NOM characteristics and the corresponding required GAC media properties are influenced by the position of the adsorption process in the treatment scheme. The study of Golea et al. (2020) correlates GAC properties, specifically the media pore size distribution, with NOM and DBPFP removal from two water sources having differing NOM chemistry with reference to DBPFP. The removal efficiency of C-DBPs is further enhanced when GAC is preceded by pre-oxidation with ozone, which converts hydrophobic NOM into more biodegradable forms that are more easily adsorbed.

In a systematic study by Erdem et al. (2020) pre-chlorination followed by a GAC contactor with a high mesopore surface area reduced DBP formation by 58 %. In another case, Huangpu River water treated through an integrated ozonation–biologically activated carbon (O_3/BAC) process showed that the BAC stage (using GAC) removed about 27 % of the trihalomethane formation potential (THMFP), contributing to a cumulative reduction as high as 74 % through the full treatment train (Wu et al., 2013).

The study of Ackey et al.(2016) aimed to evaluate the removal of natural organic matter (NOM) and the reduction of chlorinated disinfection by-products (DBPs) through biofiltration. The effects of different filter media—zeolite, sand, and granular activated carbon (GAC)—as well as contact time, were assessed using Porsuk River water (PW) from Eskisehir, Turkey. Among the tested media, the GAC column exhibited the highest removal efficiency for both trihalomethane formation potential (THMFP) and haloacetic acid formation potential (HAAFP). Specifically, the GAC biofilter achieved a 64% reduction in dissolved organic carbon (DOC), resulting in approximately 68% and 64% decreases in THMFP and HAAFP, respectively, within 30 minutes. In contrast, the zeolite and sand columns were less effective, lowering HAAFP by only 27% and 21%, respectively.

Since using of some conventional treatment processes such as coagulation, sedimentation and sand filtration are not completely efficient in the removal of organic matter, several studies have been carried out and used membrane filtration (Ultrafiltration, nanofiltration, reverse osmosis) to remove NOMs or its fractions from various water (Zazouli and Kalankesh, 2017). However, high cost and energy consumption can limit their application in developing regions.

Optimization of Disinfection Processes

One strategy to limit the formation of certain DBPs is to lower both the chlorine dose and the pH so that the proportion of hypochlorous acid (HOCl) remains high and the disinfection efficiency is maintained, since HOCl is a much stronger disinfectant than OCl^-. Several studies have shown that chlorination at pH values below 7 leads to a decrease in THM concentrations, while the formation of HAAs may either increase or decrease depending on the characteristics of the source water (Bougeard et al., 2010; Liang and Singer, 2003).
Therefore, it is important to maintain a neutral pH level (around 7.0) in water treatment processes to minimize the formation of harmful DBPs (Kalita et al., 2024). This can be achieved through the pH adjustment and control during the water treatment process.
By reducing excessive chlorine application and carefully controlling contact time (along with pH), utilities can significantly lower DBP formation.

Alternative disinfectants

Using disinfectants that produce fewer by-products can be effective. For example, chloramine, ozone, permanganate and ultraviolet (UV) light can reduce the formation of certain DBPs compared to traditional chlorine treatment, though each has its own limitations and secondary by-products.

Chloramine, formed by the reaction of chlorine with ammonia, is widely used as a secondary disinfectant in drinking water treatment. Compared to free chlorine, chloramine produces significantly lower levels of THMs and HAAs (Hua and Rekhow (2007). However, chloramine itself can form N-nitrosodimethylamine (NDMA), a potent carcinogen, under certain conditions, making it essential to monitor its application carefully. Moreover, chloramine is less effective as a disinfectant in certain water quality conditions.

UV treatment of drinking water could effectively eliminate pathogens without forming DBPs typically associated with chlorine-based treatments. However, UV disinfection does not provide residual disinfection, so the treated water could be vulnerable to microbial re-contamination during distribution.

Several studies have shown that ozone is effective in reducing the formation of THMs and HAAs in comparison to chlorine. However, while ozone is effective at removing organic precursors, it does not provide residual disinfection, which means additional disinfection steps are often required. Ozone is also associated with the formation of secondary by-products such as bromate, aldehydes and organic acids, which must be carefully monitored.

The combination of an ozonation step and biological activated carbon (BAC) filtration following a conventional treatment process (coagulation, flocculation, sedimentation, and sand filtration) reduces the chlorine demand limits the formation of disinfection by-products during chlorination (Chu et al., 2012).

The use of ozone as a pretreatment method in Algerian water treatment plants presents a viable alternative to traditional prechlorination. In Algeria, the Oued Athmenia and Aïn Tinn drinking water treatment plants, both located in Mila province, are equipped with an ozonation process (Achour and Chabbi, 2017). This approach helps reduce the formation of chlorinated by-products, particularly trihalomethanes (THMs), which are a common concern when chlorine is used in the treatment process.

Chlorine dioxide is widely used as a primary disinfectant and for distribution worldwide due to its faster oxidative and disinfectant action compared to chlorine, as well as its greater stability (Mzinyathi et al., 2025). It does not form organohalogen by-products, and its effectiveness is not dependent on pH levels. However, there are several limitations to its use, particularly in Algerian treatment plants. Chlorine dioxide can produce toxic inorganic by-products, such as chlorite and, to a lesser extent, chlorate. Additionally, it tends to be more expensive than chlorine and is more difficult to handle.

Potassium permanganate is another alternative oxidant used to treat water. Researches (Singer et al., 1980; Guan et al., 2010) found that potassium permanganate, when used as a pre-oxidant before chlorination, reduced the formation of THMs and HAAs in drinking water. Pre-oxidation strategies, such as the use of permanganate, have been shown to reduce the formation of dichloroacetonitrile (DCAN) and trichloronitromethane (TCNM) by oxidizing algal organic matter prior to chlorination (Chen et al., 2023).

In Algeria, some treatment plants use potassium permanganate during pre-treatment, but primarily for its oxidative purpose to mainly eliminate algae, iron, and manganese (Boudouaou, Ain Tin, Koudiet Medouer).

The study of Achour and Guergazi (2013) have examined the use of permanganate as a replacement for prechlorination to reduce water reactivity and the potential for chloroform formation. Algerian surface waters were preoxidized with potassium permanganate ($KMnO_4$) at variable concentrations for 2 hours, followed by chlorination at 20 mg/L. After 24 hours, chlorine demand was measured. The results revealed that higher doses of permanganate pre-treatment led to a significant reduction in chlorine consumption and a decrease in chloroform production, compared to waters treated with chlorine alone. The reduction in chloroform formation varied from 10% to 70%, depending on the amount of permanganate applied and the water source.

Similarly, the results from the study of Achour and Afoufou (2002) showed that humic substances have significant reactivity towards both chlorine and potassium permanganate. The chlorine and $KMnO_4$ consumption potentials increased with higher SH concentrations. While the mineralization of the SH dilution medium seemed to enhance their reactivity, the influence of pH differed depending on the type of oxidant. The formation of aromatic substances with carboxyl groups, which are less reactive towards chlorine, could explain the reduced chlorine consumption observed when combining $KMnO_4$ preoxidation with post-chlorination.

Furthermore, experiments of Afoufou and Achour (2002) demonstrated that oxidation treatments of SH had a significant impact on coagulation-flocculation. In the case of prechlorination, this was linked to the formation of organohalogen compounds with

carboxyl groups and the creation of THMs. For $KMnO_4$ preoxidation, the by-products formed were difficult to coagulate, either due to their small molecular size or chemical structure.

Based on both literature and experimental results (Afoufou and Achour, 2002; Achour and Guergazi, 2013), the addition of potassium permanganate can be proposed as a viable alternative to prechlorination for Algerian water treatment. While potassium permanganate may not be a complete solution, it can effectively reduce THM concentrations when used in combination with other treatment methods. Additionally, permanganate helps eliminate manganese, taste and odor compounds, and can aid in controlling algae and other aquatic growths.

Post-formation DBP removal methods in water treatment

The removal of DBPs after their formation can be challenging to implement in water treatment plants, depending on the method (Sun et al., 2019; Jiang et al., 2017; Xiao et al., 2023):

- Aeration is effective for removing volatile DBPs like THMs by allowing them to escape from the water into the air. It's a simple, cost-effective method but works best for certain DBPs that are volatile at the treatment plant's operating conditions.
- Activated Carbon Adsorption is widely used and relatively easy to implement, but requires regular maintenance and may not remove all types of DBPs effectively.
- Advanced Oxidation Processes (AOPs) and UV Irradiation are effective but more complex and costly to install and operate, with high-energy demands and the need for regular maintenance.
- Reverse Osmosis (RO) is highly effective but expensive, energy-intensive, and requires regular maintenance, making it suitable mainly for specialized or smaller-scale applications.
- Distillation is energy-intensive and impractical for large-scale use.

CONCLUSION

This work demonstrates that the formation of disinfection by-products is an inherent consequence of chemical disinfection, particularly in chlorine-based treatment systems, and represents a complex global challenge at the interface of water treatment engineering, environmental chemistry, and public health. DBP formation is governed by multi-factorial interactions between source water characteristics (quantity and quality of NOM, halide and nitrogen content), disinfectant type and conditions, and climatic and hydrological context.

While international regulations predominantly target THMs and HAAs, these compounds represent only the visible fraction of a much larger pool of halogenated and nitrogenous DBPs. Experimental evidence, including Algerian reservoir studies, clearly shows that the majority of halogen incorporation occurs in non-volatile, under-monitored DBP

classes, many of which exhibit higher toxicological potency. This highlights a critical gap between regulatory practice and current scientific knowledge.

The Algerian case provides a representative model of challenges faced by semi-arid and developing regions: increasing reliance on degraded surface waters, elevated organic and bromide loads, strong chlorine demand, and limited systematic monitoring capacity. The observed spatial variability in THM speciation—from predominantly chlorinated forms in northern waters to more toxic brominated species in southern basin waters—demonstrates the necessity of region-specific treatment and monitoring strategies.

Current treatment experiences in Algeria show that DBP formation is not inevitable. Improved precursor removal via enhanced coagulation, careful control of operational parameters (pH, dose, contact time), and the integration of alternative oxidation processes such as ozonation or potassium permanganate, coupled with biological activated carbon, can significantly reduce both chlorine demand and DBP formation potential. However, such interventions must be carefully designed to avoid secondary by-products such as bromates or nitrosamines.

From a public health standpoint, the convergence between widespread DBP exposure and the statistically documented increase in cancers potentially linked to DBPs—particularly bladder and colorectal cancers—does not establish causality but reinforces the plausibility of a contributing environmental factor. This is especially relevant in Algeria, where systematic DBP exposure assessment and population-level epidemiological studies remain limited.

In conclusion, future efforts in water safety management must move beyond single-compound regulation and adopt a more integrated risk-based framework. This includes:
(i) Systematic monitoring of both regulated and emerging DBPs,
(ii) Better characterization of precursor chemistry and water reactivity,
(iii) Optimization of multi-barrier treatment schemes adapted to regional conditions, and
(iv) Stronger integration between water quality data and public health surveillance.

Such an approach is essential not only for Algeria but for all regions facing increasing pressure on water resources under climate change, urbanization, and environmental degradation, to ensure that the benefits of disinfection are not compromised by avoidable long-term chemical risks.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could influence the work reported in this article.

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