FORMATION OF BROMATE IN PET BOTTLE WATER

by

Haifa Sharif

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Approval Signatures

We, the undersigned, approve the Master’s Thesis of Haifa Ismail Mohammad Sharif.

Thesis Title: Formation of Bromate in PET Bottle Water.

Signature **Date of Signature**
(dd/mm/yyyy)

Dr. Md. Maruf Mortula
Associate Professor
Department of Civil Engineering
Thesis Advisor

Dr. Serter Atabay
Associate Professor
Department of Civil Engineering
Thesis Advisor

Dr. Kazi Parvez Fattah
Assistant Professor
Department of Civil Engineering
Thesis Committee Member

Dr. Fatin Samara
Assistant Professor, Department of Biology,
Chemistry, and Environmental Sciences
Thesis Committee Member

Dr. Osman Akan
Head, Department of Civil Engineering

Dr. Hany El-Kadi
Associate Dean, College of Engineering

Dr. Leland Blank
Dean, College of Engineering

Dr. Khaled Assaleh
Director of Graduate Studies

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This work is dedicated to my parents, the reason for my existence

Abstract

High bromate levels in bottle water is a concern in UAE. In this study, bromate formation in bottles of drinking water was studied while exposed to various temperatures, storage times and pH levels. Three brands, referred to as X, Y and Z, were selected to reflect the local, regional and international water bottles supplied in the United Arab Emirates (UAE). From each brand, 36 Polyethylene terephthalate (PET) bottles of water were collected. Moreover, four different temperatures were selected based on the weather conditions in the UAE. These temperatures are 20°C, 30°C, 40°C, and 50°C. The water bottles used in the study were stored in incubators at 3 storage times which were 1 day, 14 days and 42 days. They were also introduced to three pH levels which are 6.5, 7.5 and 8.5. Bromate, turbidity, TDS and total bacterial count (TBC) levels were tested for all the samples of bottles. Besides, additional parameters, bromide and total organic carbon (TOC), were tested for 12 samples at 42 days. The results of the study showed that bromate was found in all tested brands at 1 day storage time. It was also found in brands X and Y at 14 days and 42 days storage time. On the other hand, brand Z had no traces of bromate at 14 days and 42 days storage time. Increasing the storage time in general tended to reduce bromate levels in water. Regardless of the storage time and the pH level of the water, the effect of temperature was negligible for all tested brands. Furthermore, compared to the temperature and storage time, the pH effect on bromate formation was much more noticeable. Increasing pH level caused an increase in bromate formation in brands X and Y. However, Brand Z observed a decrease in bromate formation with pH level increase. Brands X and Z had no correlation between bromate and bromide. Brand Y; nevertheless, observed a decrease in bromate formation with an increase in bromide concentration. Other water quality parameters including TDS, TOC, turbidity and TBC effect on bromate formation was not significant. Regardless of the conditions water bottles were exposed to, all bromate levels were found to be below the maximum contamination level, 10µgL, set by several organizations.

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1. Introduction

1.1 Background Information

Drinking water is a finite and valuable resource that is vital for nourishing health and life. Whether water is bottled or supplied through taps, it is a very important part of daily life [1]. Ensuring good quality water resources is also critical for ecosystems preservation. There is an evidence of a growing crisis regarding global drinking water [2]. The crisis threatens sustainable development, life, security and peace [2]. Rapid urbanization, economic development and changing lifestyles have led to an increase in water demand which caused a remarkable pressure on the existing water resources [3]. More than one billion people around the world lack access to safe drinking water; as a result, consuming contaminated water has led to an estimated 80% of children death [2].

Taste in general does not necessarily indicate whether the water is safe to drink or not. However, it is often perceived as an indicator for water quality. Calcium and magnesium add a distinctive flavor to water, yet they are considered to be essential to human bodies [4]. In addition, treatment methods used to treat the water can affect its taste and quality. In particular, using disinfectants, such as chlorines, ozone or chloramine adds a distinguishable taste to the water. Besides, chlorine and chloramine are widely used to disinfect tap water due to its effectiveness and low cost compared to other disinfectants. These chemicals continue to travel through the distribution systems to consumers' houses. Ozone; on the other hand, is more preferred to disinfect packaged water. Although it is considered to be more expensive, companies of water bottles prefer to use it since it does not leave a taste like chlorine.

Although bottled water price is considered to be very high compared to municipal tap water, it is still the preferable type for plenty of people. Several factors have helped in the increase in bottled water consumption, such as public concerns regarding harmful components in municipal drinking water supplies [2]. Additionally, the lack of easily available safe drinking water has also led to the increase in bottled water consumption. Bottled water is perceived as pure and safe for public health compared to other sources of potable water. Furthermore, effective advertising and marketing strategies that suppliers of bottled water use have significantly increased the demand on bottled water [5]. In addition, bottled water is widely accepted due to the convenience and the taste it provides [6].

Consumption of bottled water has been significantly increasing within the last three decades. Bottled water market is predicted to be worth US$ 220million with an annual volume of 890 million liters [4]. The world's main bottled water consumers are Western Europeans with an annual consumption of 85L/person. A total of 12 out of 20 leading bottled water consumers are from the European Union (EU). The Pacific and Asia are considered to be the most promising markets [4]. Recent studies show that the United States of America (USA) contributes to 15.8% of global consumption of bottled water [7]. Markets of water bottles grow by almost 10% every year in the USA which has made it the second most popular beverage after soft drinks. In 2005, the average population of the USA consumed 194L (51.5gal) of soft drinks and 94.6L (25gal) of water [8]. Furthermore, countries with the highest consumption of bottled water are noted to be the ones with the safest tap water supply [2]. Figure 1.1 [9] shows bottled water consumption per capita by leading countries around the world for the years 2006 and 2011.

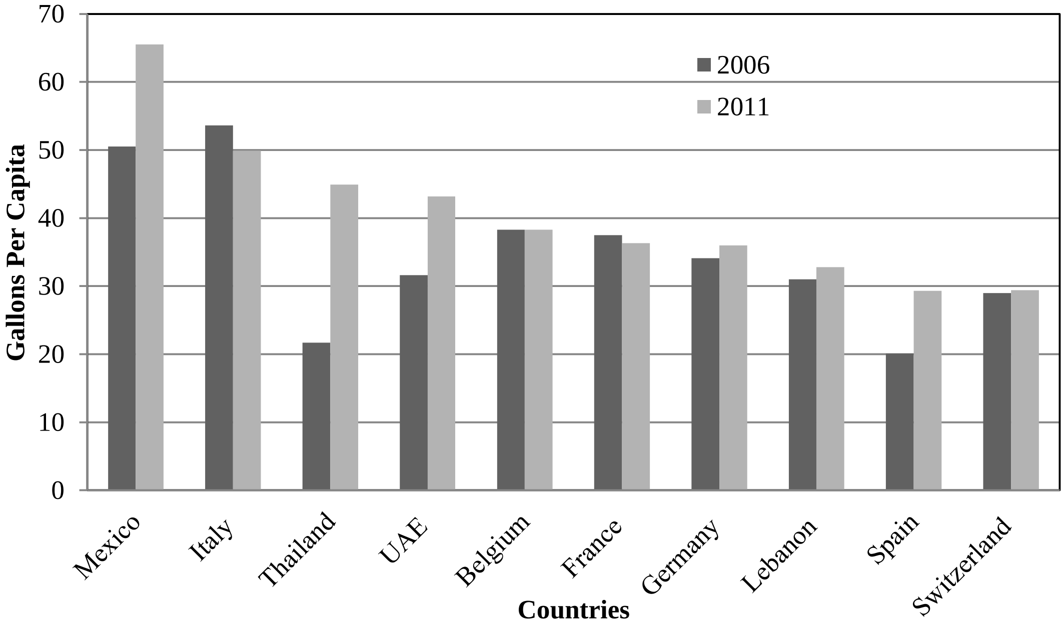

Figure 1.1: Global bottled water consumption **[9]**

Figure 1.1 indicates that Mexico is the leading country followed by Italy, Thailand and the UAE. Nonetheless, Mexico tops the annual global per-capita bottled water consumption with almost 234L/capita [7]. This might have occurred due to the increase in population as well as lack of running water in Mexico. On the other hand, the decrease in bottled water consumption in France might have resulted from the lack of awareness of safe tap water. Switzerland and Belgium consumption remained the same regardless of the population growth.

Water supply in the UAE comes from two main sources which are groundwater and desalinated water. It is worth noting that groundwater is very limited as it depends on rainfall which is limited in the country; in addition, desalinated water is delivered at very high cost [10]. Bottled drinking water is widely advertised for in the UAE as well as in the Arabian Peninsula. Water bottles consumers in the UAE purchase water in different serving sizes, between 100mL to 5gal. A large quantity of bottled water is consumed daily by the population of the UAE due to the region's very high temperatures, low humidity and lack of free flowing water. In addition, it is socially the only acceptable form of drinking water. In the UAE, around 90% of the population depends on bottled drinking water for their daily consumption [11]. Table 1.1 shows bottled water consumption over time in the UAE [12]. The high consumption of bottled water in the UAE has led to it becoming among the top country of consumers of bottled water around the world. Bottled water demand in the UAE has been increasing within the last few years as shown in table below.

Table 1.1: Bottled water consumption in the UAE [12]

	2008	**2009**	**2010**	**2011**	**2012f**	**2013f**	**2014f**	**2015f**
UAE (AED mn)	1,914	2,028	2,090	2,196	2,342	2,532	2,749	2,986

f:forecast

1.2 Problem Statement

Bottled drinking water quality varies from one place to another depending on the sources of water and treatment processes used for purification. Different standards are introduced around the world to regulate the quality of bottled water; however, there are some chemicals that are regulated in tap water and not in bottled water [8]. Although bottled drinking water is used extensively, it may not be as safe as consumers’ perception. This is due to the leaching of different harmful chemicals from the plastics and polymers used to synthesize the bottles of water. The leached chemicals can pose serious health threats to the public that rely on bottled water as the principal drinking water source. Recently, the scientific community around the world is concerned and started to deal with the existence of toxic contaminants in water contained in plastic bottles [13].

Since most of the water bottle brands in the UAE depend on ozonation process to treat its water, bromate was found in various local brands supplied in the country [14]. In some local brands, bromate was found to have exceeded the World Health Organization (WHO) allowed MCL of 10µg/L. Famous brands, such as Masafi water bottles, were recalled from the market in 2012 as they exceeded the allowable bromate levels [14]. The fact of bromate being found in drinking water supplied in the UAE is of a concern to the public since bromate could cause cancer in the long run. It is worth stating that the second leading cause of death in the UAE is cancer [15]; therefore, any reason that might be linked to cancer must be investigated carefully, including bromate.

1.3 Objectives

This research mainly aims at studying the formation of chemicals from PET water bottles supplied in the UAE. The two major objectives are:

- To assess the formation of bromate from PET water bottles
- To assess the effect of temperature, pH change and storage time on the water and concentration of bromate formed

2. Literature Review

2.1 Packaged Water

There are different sources of packaged drinking water. Artesian water comes from a natural or artificial well which taps water through a confined aquifer. Ground water is not directly influenced by surface water; it comes from a subsurface saturated region. Mineral water, which comes from groundwater, contains total dissolved solids (TDS) with a minimum value of 250ppm [8]. TDS is mainly due to the presence of calcium, magnesium, sodium, potassium and silica. In addition, sparkling bottled water originates from a spring where it is naturally carbonated. Carbon dioxide can be added if water carbonation is lost during processing. Purified water is free from all types of chemicals; however, it does not necessarily have to be free of microbes [8]. Purified water source is typically not shown on the water label. It can be classified as per the purification method used. Purified drinkable water includes distilled water, demineralized water, reverse osmosis water and deionized water. Moreover, spring water originates from groundwater that flows naturally to the surface of earth. Sterilized water is free of all kinds of microbes and has to pass through all sterility tests of the US Pharmacopeia. Additionally, well-water comes from a constructed hole in the ground that passes water through an aquifer. Purified water and bottled spring water are considered as the most common types of drinking water consumed in the US [8].

The US Food and Drug Administration (FDA) also defines bottled water as products that are labeled as bottled water, artesian water, drinking water, mineral water, sparkling bottled water, spring water and purified water. The FDA regulates other types of water including soda water, tonic water, flavored water, vitamin enriched water and carbonated water as soft drinks [16].

2.2 Types of Water Bottles

Table 2.1 describes different types of bottles that are used for different needs [7]. Among them, Polyethylene terephthalate (PET) is the most common packaging used for water bottles worldwide. Different types of bottles are used for different norms. High-density polyethylene (HDPE); for example, is used for detergent and shampoo bottles and is considered a very safe as well as recyclable type of plastic. However, HDPE is only good for short term usage. On the other hand, CD cases, grocery bags and other bottles are made from Low-density polyethylene (LDPE). The disadvantage of LDPE is that it is non-recyclable and is only good for short term usage as well. Polypropylene (PP) is used for disposable food containers, medicine bottles, reusable plastic food containers and bottles. It is suitable for reuse, and it is non-leaching but only good for short term use. Take-out food containers, cups and packing material are usually made from polystyrene which cannot be reused or recycled. Polystyrene leaches styrene, a carcinogenic toxic chemical; thus, polystyrene is an unsafe material. Polyvinyl chloride (PVC) is used for plumbing pipes, bottles, plastic binder coverings, shower curtains and wrappers on cheese and meat products. This type of material has caused numerous controversial issues since it releases a great amount of toxins during its manufacturing which adversely affects the environment. The majority of water bottles are made from polyethylene terephthalate (PET). PET is recyclable and is safe to be used.

Additionally, bottles can be made from other materials, such as metal, aluminum and glass. The main disadvantage of these three types is that they are heavy materials and are not user friendly. However, using such materials can assure consumers that the water is fresh and free from any chemical leaching.

Table 2.1: Bottle types **[7]**

Type of Bottle	**Description**
Polyethylene terephthalate (PET)	Majority of water bottles are made using this type of plastic. However, this type is not intended for using more than once as reuse can cause bacterial growth.
High-density polyethylene (HDPE)	This type is used for detergent bottles, shampoo bottles, shopping bags, and some types of plastic toys. This type is considered to be one of the safest plastic types being used and is also considered to be recyclable.
Polyvinyl chloride (PVC)	This type is used for plumbing pipes, bottles, plastic binder coverings, shower curtains and wrappers on cheese and meat products. However, this type is not considered to be environment friendly as many toxins are released into the environment during its production.
Low-density polyethylene (LDPE)	This type is highly used for CD cases, grocery bags, 6-packs of cans plastic rings, and bottles.
Polypropylene (PP)	This type is used for disposable food containers, medicine bottles, reusable plastic food containers, and bottles.
Polystyrene	This type is used for take-out food containers, cups, and packing material.
Metal water bottles	This type of bottles retains minimal taste and odor from its content yet it readily transfers contents temperature to external surfaces. Therefore, they are considered to be unsuitable with very cold or very hot liquids. This type is also very heavy compared to plastics.
Aluminum bottles	This type contains epoxy liner or plastic resin which protects taste and odor transfer from contents.
Glass bottles	This type is recyclable, transfer minimal odor and taste, and BPA free. However, this type is also heavy and readily transfers contents temperature to external surfaces.

2.3 PET Bottles

PET ($C_{10}H_8O_4$) is the most common packaging material used around the world for holding drinking water as well as soft drinks. PET bottles usage for beverages has increased significantly since it is being used for energy drinks, ice tea and beverages like juice, beer and wine. PET bottles light-weight and collapsibility compared to other types of bottles have helped in increasing its demand. They are manufactured using one-step injection stretch blow-molding process [17]. PET has a good moisture and oxygen barrier property as compared to other packaging polymers. It has replaced various packaging materials, such as glass and metal cans [18].

Nowadays, PET is manufactured without the use of Bisphenol A. This means that PET water bottles are safe for consumers since no leaching of this chemical could be found. In addition, heavy metals, such as cadmium, lead and mercury, are not used in the manufacture of PET. Instead, low toxic non-metallic antimony, antimony oxide, is used in its manufacture. Because of the low toxicity and low occurrence of antimony oxide, the PET bottles are safe not only for consumers, but also for the environment [18].

2.4 Brominated Compounds

Brominated compounds have been found to leach in PET water bottles. However, studies show that inorganic brominated compounds, such as bromate, brominated acetic and brominated halomethanes, which are common disinfection byproducts, may be present in water even before bottling it. Different water treatment processes can cause inorganic brominated compounds to be formed in water. High levels of total bromine were reported in 70 water brands in Turkey [7].

People are mainly exposed to bromate through drinking water. In addition, eye contact with water containing bromate through bathing or face washing can expose people to bromate. Bromate is not normally found in drinking water; bromide might be converted to bromate during ozonation process. The conversion of bromide to bromate process is affected by pH, temperature, natural organic matter and other factors. Bromate is considered as a potential human carcinogen. Unlike other organic by-products, bromate does not biodegrade in biological filters [19]. Formation of bromate might increase with temperature increase [20]. A study conducted by

Siddiqui, Amy and Rice on alkalinity effect on bromate formation during ozonation show that an increase in alkalinity causes an increase in bromate formation [21].

In concentrated hypochlorite solutions used to disinfect drinking water, bromate might be formed. This reaction occurs because bromide exists in raw materials, such as sodium hydroxide and chorine used in sodium hypochlorite manufacture. Chlorine dioxide is not used to oxidize bromide; therefore, chlorine dioxide will not form bromate, hypobromite ion or hypobromous acid. Bromate can be formed if exposed simultaneously to both chlorine dioxide and light [22].

According to the WHO, the Japanese Ministry of Health, the European Commission and the Environmental Protection Agency (EPA), bromate MCL in drinking water treated by ozonation is 10μg/L. However, European Commission MCL for bromate in natural mineral and spring waters disinfected by ozonation is 3μg/L [23].

2.5 Bromate Formation

Bromate, an alleged carcinogen, is a product resulting from the ozonation process of water that contains bromide. Understanding the bromate formation mechanisms is significant when assessing the tools used to control the bromate formation. The possible development of by-products from ozonation may limit the use of ozone (O_3), a potent disinfectant. Adding ozone to water results in the formation of ozone residuals as well as hydroxyl (HO) radicals. The existence of O_3 and HO is directly linked to bromate formation. Furthermore, bromate formation is affected by the presence of natural organic matter (NOM) since NOM reacts with O_3 and HO to form bromate [24].

The ozone dose used affects the formation of bromate. A study pointed out that no bromate was found when no residual ozone was present in water [25]. Moreover, another study found a steady increase in bromate levels as the ozonation process continued [26]. This reaction occurs until all the bromide in the water in transformed into bromate. Therefore, total oxidation of bromide to bromate occurs when ozonation is continued [27]. Whereas, a different study showed that when the ozone to total organic carbon (TOC) ratio reaches 1, bromate is then detected [28]. In addition, another study indicated a reduction in brominated organic by-products as the ozone dose increases [27].

A study conducted by Richardson that examined the production of bromate from ozonated sea-water under light and dark conditions indicates that no variances were witnessed during the actual ozonation process [29]. Nevertheless, after the ozonation process was completed, a slight increase in the bromate concentration was found in the samples that were exposed to sunlight [27]. Furthermore, Haag and Hoigne examined the reaction between bromide and ozonation thoroughly [30]. The overall reaction scheme is shown in the following reactions [27] :

$$O_3 + Br^- \rightarrow 2O_2 + BrO_3^-$$

$$\text{Oxidizing agent} + Br^- \rightarrow BrO_3^-$$

2.6 Conditions Affecting the Leaching Process of Chemicals in PET Bottles

Several factors affect chemicals leaching from PET water bottles into water. Temperature is considered to be one of the leading factors. A higher rate of chemicals leaching into water bottles into the water were the ones exposed to higher temperature [31]. A study by Westerhoff was conducted to check the behavior of temperature and leaching of antimony. The temperature used in the study ranged between 22 ºC and 80 ºC. Results show that as the temperature of the stored water bottles increased, a higher concentration of antimony was found in the water [32] .

The effect of exposing PET bottles to sunlight was less significant than other factors causing chemicals leaching into drinking water. Storage of PET bottles at outdoor conditions was studied by Diana. Outdoor conditions refer to the exposure of PET water bottles to sunlight irradiation and various temperatures for 15 to 30 days. Diana's study shows that outdoor conditions factor does not have a significant influence on chemicals leaching into bottled drinking water [33]. Another study was conducted by Cheng on samples exposed to sunlight for 7 days, where around 16 leaching metals were taken into consideration. The results of the study show that only a slight increase in the antimony concentration level of the water samples occurred. The study also suggests that the effect of leaching antimony due to sunlight and irradiation is very minor [34]. In addition, the results indicate that the clarity of PET bottles has an effect on chemicals leaching into drinking water. Besides, clear PET bottles were observed to have less chemical leaching than those of colored ones [35]. A study by Westerhoff show that storage time affects leaching of chemicals into PET bottles. It indicates that the longer the bottles are stored, the higher probability of chemicals leaching into the drinking water results [32]. Moreover, pH has an effect on chemicals leaching into PET water bottles. Sparkling water was studied against still water; it was realized that sparkling water antimony leaching was higher than that of still water [36]. Furthermore, another study was conducted by Cheng to check the behavior of lower pH liquids. Water with pH of 4 was used to mimic low pH liquids. The results indicate that lower pH levels caused higher release of Sb into drinking water [34].

2.7 Limitation of Leached Chemicals Based on Standards

Since the early 80’s, a number of international regulations were set to monitor and limit toxic chemicals use in water bottles. Different regulations from local to international levels are set. The EPA regulates tap water that is meant for drinking purposes; the U.S. FDA; on the other hand, regulates drinking bottled water. The FDA regulates and monitors various products of bottled water under its food safety program. In some cases, bottled water regulations are much more stringent as compared to tap water regulations. Manufacturing practices are set by the FDA to regulate bottled water. Producers are thereby required to follow several procedures. Bottled water shall be processed, bottled, held and transported under sanitary environment. Additionally, bottled water sources shall be protected from chemicals, bacteria as well as other contaminants. Quality control processes shall also be used to ensure chemical and bacteriological safety of bottled water. Finally, source water and final product shall be both sampled and tested for contaminants [16].

Bottled water standards of identity have been issued by the FDA. Uniform definitions and requirements were set for the following bottled water classifications: drinking, deionized, mineral, ground, artesian, distilled, sparkling, well, spring, purified and reverse osmosis water. Standards of identity are required federally to classify drinking water in the market. Quality standards have also been set by the

FDA for more than 90 substances in bottled water. The FDA’s quality standards for bottled water are very similar to the EPA’s maximum contaminant levels (MCL) for tap water. According to the EPA, the MCL level of antimony and bromate of tap water are 6μg/L and 10μg/L respectively. For tap water, the public health goal is to have 6μg/L of antimony and 0μg/L. The amount of antimony found in tap water will not affect human’s health as much as the bromate. The main risk with bromate is that it could cause cancer in the long run. This is due to the contamination of tap water by the byproducts released during the process of disinfecting drinking water [37].

There are very few differences between the quality standards of the EPA and the FDA; the differences occur since some of the substances regulated in tap water are not found in bottled water. Bottled water is regulated under the food additives program of the FDA. Although the regulations of the FDA and the EPA are to be followed in the US for bottled water, some states or provinces in North America have set more stringent requirements than those set by the EPA or the FDA [38]. According to Water Quality Product Magazine, Massachusetts and Quebec are examples where local regulations are more stringent and broader than federal regulations [39].

In 1985, the WHO published the first edition of Guidelines on Drinking Water Quality. Various contaminants were regulated in the guidelines, such as physical, chemical, radiological and microbiological contaminants. Later on, in 1992, an updated version of the guidelines was issued with reference to more than 200 experts from more than 40 countries around the world. Several countries used these guidelines to establish their drinking water standards on a national level [39].

Packaged water international framework regulation is set by Codex Alimentarius Commission (CAC) of the WHO and the Food and Agriculture Organization (FAO). With the aim of helping in facilitating international trade of bottled water, CAC has developed different international standards to regulate bottled water. Standard for Natural Mineral Water along with an associated Code of Practice were set to regulate the product quality factors and its components as well as certain chemicals limits. In addition, Standard for Bottled/Packaged Waters has been developed by CAC to regulate bottled water other than mineral water [40]. The EPA and the WHO standards are similar for identified analytes. On the other hand, volatile and semi-volatile standards differ. The EPA regulates 62 volatile organic compounds; whereas, the WHO regulates only 29. However, regulations of the WHO towards semi-volatile compounds are more stringent than these of the EPA. Unlike the EPA, the WHO regulates disinfection-by-products. Its regulations were developed to be applied internationally; therefore, it regulates more compounds than the EPA.

Water bottlers in the UAE must follow GSO/UAE Standard No. 1025/2009. This standard was developed in accordance with Dubai Municipality Standard (DMS) No. 027. In order for water bottlers to comply with DMS 027 requirements, they should have a quality assurance laboratory for various factory production control tests. The laboratory should at least have resources and equipment to perform sensory, microbiological and physical tests. Sensory tests include color, odor, taste and turbidity tests. Microbiological tests include total coliform, Pseudomonas Aeruginose and total bacterial count. Physical tests include pH, total dissolved solids (TDS), total hardness, chloride, sulphate, fluoride, iron, magnesium, calcium, nitrate, chlorine, ozone and bromate tests. Moreover, bromate must be measured in ppm. Water bottlers should also follow ISO 9001 quality management system in the UAE. Moreover, they are required to follow good manufacturing practice, hazard analysis and critical control points system and to regulate their water bottles as per the GSO 1025/2009 standards [41].

Although the FDA regulates bottled water, it does not certify it. Bottled water consumers may notice a seal or logo from other organizations placed on the water bottle label. IBWA; for instance, certifies water bottles. Water bottlers must meet IBWA model code in order to become an approved member. In addition, they must pass third party annual inspection, which is hired by IBWA. IBWA works with the FDA to make sure that water bottles meet the high standards needed by setting strict regulations. Water bottlers mostly reflect their membership to IBWA on their water bottles labels. Another organization certifying bottled water is the National Science Foundation (NSF). In order for water bottlers to certify their product by the NSF, their bottled water must go through additional unannounced annual tests and inspections. All the requirements of the FDA must be met in order for the bottled water to be certified by the NSF. Furthermore, among the laboratories that conduct the bottled water testing is Underwriters Laboratories (UL). UL is a certification and independent accredited testing organization that conducts tests based on the FDA, IBWA model code and state standards [42].

2.8 Composition of Drinking Water Supply in the UAE

Experts in the UAE endorse that municipal tap water supplied in the country is treated by desalination and is considered to be a safe option for drinking water. However, the UAE residents still prefer to rely on bottled drinking water for their daily consumption. Among the most known brands manufactured in the country are Oasis, Masafi and Al Ain. Bottled water business has been growing in the UAE as the demand has increased within the past few years [43]. Bottled mineral drinking water is extensively marketed in the UAE. PET annual consumption is about 80,000 tons in the UAE. Furthermore, one ton of PET is equivalent to 40,000 bottles. This huge consumption has led the country to become among the highest consumers of PET bottles around the world [44] .

PET bottles are widely used by potable water suppliers in the UAE. The composition of water supplied from different water companies is shown in Table 2.2. The pH range for bottled water supplied by different water companies is 6-8. In addition, bottled water has very low total dissolved solids (TDS) ranging between 25-150 ppm. The total hardness of the bottled water is within the acceptable ranges. Moreover, the content of minerals varies significantly from one company to another.

Table 2.2: Composition of drinking water supply in the UAE

No.	**Water Company Name**	**pH**	**TDS (ppm)**	**Calcuim (ppm)**	**Magnesium (ppm)**	**Sodium (ppm)**	**Chloride (ppm)**
1	Aquafina	7	110	<5	13	16	-
2	Oasis	6.8	120	19.5	6.5	16	50
3	Spring	7.2	115	6	1	10	45
4	Masafi	7.8	130	3.4	19	10	-
5	Awafi Mineral water Co.	7.6	120	3.1	17	22	56.6
6	Marina Water	7.8	110	30	12	<5	25
7	Silver Spring Water	7	120	20	15	9	40
8	Sana Water	7.3	110	13	8	8	40
9	Nestle Water	6.3	100	5 - 14	2.8 - 5	5.4 - 11	9.2 - 25
10	Dubai Water	7.9	25 - 150	-	15	-	50

3. Materials and Methods

3.1 Materials

Bottles from three different water brands, referred to as X, Y and Z, were used to conduct the experiments. All the bottles were made of PET. From each brand, 36 PET bottles were collected. The size of the selected bottles was 500mL since it is the most common size consumed.

Brand X is one of the leading suppliers of bottled drinking water in the UAE. It was chosen to represent local bottled water companies. It originates from natural mineral water source which comes from underground springs in Ras Al Khaimah, UAE. This brand is not only found in the UAE, but also found in a number of other Arab Countries. It is certified by several organizations including Asia Middle East Bottled Water Association (ABWA) that conducts plenty of tests against its own model code, Codex Alimentarius, FDA and WHO. Brand X is also internationally certified by the NSF. Moreover, brand X water is considered to be microbiologically wholesome since it contains natural mineral salts as well as other constituents. The mineral composition of this brand consists of Magnesium, Sodium, Calcium and Potassium. Moreover, ozonation process is conducted for sterilization purposes where the aesthetic property of water is conserved [45].

Brand Y bottled water comes from the springs of Anatolia, Turkey. It was chosen to represent regional bottled water companies. In this band, water is transported from the source through stainless steel pipes to the bottling facilities. Hygienic conditions are ensured during the transportation process. Brand Y bottles its water by fully automated machines. In order to ensure a high quality supplied water, brand Y subjects its water to periodical microbiological and chemical tests at 40 different locations between the source and the consumption point at its laboratories. It is famous for its low sodium level which is around 1.6mg/L as shown in Table 3.1. Brand Y also claims that its water is totally bromate free. It distributes bottled water to several countries in Europe as well as the Middle East [46].

Brand Z water originates from a natural spring at the very bottom of the French Alps. It was chosen to represent international companies. The brand has maintained a unique mineral composition since 1807. Hundreds of analytical tests are performed on the quality of the source water as well as the bottled water to verify its mineral composition constantly. Moreover, in this brand, stainless steel pipes are used to transfer water from the spring to the treatment plant under sanitary conditions. Natural occurring manganese and iron are removed using Greensand Filtration. Although iron and manganese are considered to be harmless, they are removed for aesthetic reasons. Brand Z is distributed all over the world. Several standards are met by this brand. Unannounced annual inspections done by NSF on brand Z production plant certify the brand as an official member of IBWA where different standards, such as the standards of the FDA, are met [47].

Table 3.1 shows the information that was presented on the label of each brand. The production date of the brands was chosen to be as recent as available to the consumers at the market during the time of the experiments. The expiry date of all Brands is 1 year after the production date. The pH values found in the selected brands ranged between 7.1 and 7.8, where the highest pH value was observed in brand X. The TDS levels in the three brands varied radically, where brand Z had the highest level which was 309mg/L. Such levels of TDS can prompt bromate formation in water; therefore, TDS levels were studied against bromate formation. TDS consists of calcium, magnesium, sodium, potassium and silica. The highest levels of sodium, chloride and sulfate were observed in brand X to be 10mg/L, 47mg/L, and 19mg/L respectively. Brand Z had the highest amount of calcium which was 80mg/L. Not only the calcium was found to be the highest in brand Z, but also were the magnesium, bicarbonate and nitrate. Brand Y; on the other hand, showed the lowest level of magnesium to be 1.7mg/L. Moreover, silica was only found in brand Z.

Three water bottles were tested as bench marks for brands X, Y and Z. The production dates were 28/12/2013, 10/10/2013 and 20/08/2013 for Brands X, Y and Z respectively. The bench mark for bromate levels were 1.02µg/L, 1.2µg/L and Nil for Brands X, Y and Z respectively.

Table 3.1: Tested water bottles information

Parameters	**Brand**		
	X	**Y**	**Z**
Production Date	13/07/2013	11/06/2013	23/03/2013
Expiry Date	12/07/2014	11/06/2014	23/03/2014
pH	7.8	7.1	7.2
TDS (mg/L)	120-180	40	309
Sodium (mg/L)	10	1.6	6.5
Potassium (mg/L)	0.2	0.3	-
Calcium (mg/L)	3.4	8.74	80
Magnesium (mg/L)	19	1.7	26
Bicarbonate (mg/L)	27	43.9	360
Chloride (mg/L)	47	1.1	6.8
Nitrate (mg/L)	0.4	1.0	3.7
Sulfate (mg/L)	19	3.82	12.6

3.2 Methods

3.2.1 Experimental Procedure

pH level, temperature and storage time are the three factors that were changed during the experiments. Water bottles were introduced to specific pH levels. In order to decrease the pH level, hydrochloric acid (HCl) was added. The selection of HCl acid was based on its odorless and colorless properties. It was also selected since it will be the least affected by the change in temperature and storage time as compared to other available acids. On the other hand, sodium hydroxide (NaOH) was added to increase the pH level. After adjusting the pH levels, the bottles were stored at four incubators (as shown in Figure 3.1) for certain storage time. The incubators were also set at specific temperatures. After the storage time was completed, the bottles were taken out and the water samples were tested for water quality analysis.

Figure 3.1: Incubator

3.2.2 Experimental Plan

Water bottles were introduced to three pH levels which are 6.5, 7.5 and 8.5 (as represented in Table 3.2). The pH levels were chosen based on the range pH of water bottles available at the market. The incubators were set at the following temperatures: 20°C, 30°C, 40°C and 50°C. The temperatures were selected based on the weather conditions in the UAE. Temperature 20ºC was chosen since it is the average temperature water bottles are exposed to, especially during winter in the UAE. The highest temperature (50°C) chosen mainly occurs during July and August. Other temperatures were selected to realize whether temperature increase affects bromate formation or not. Moreover, the bottles were stored in the incubators at three different storage times, which are 1 day, 14 days and 42 days. The 1 day storage time was selected since it reflects the most common storage time for water bottles before being fully consumed. Whereas, the 14 days storage time reflects the average storage time, and the 42 days storage time represents extreme cases.

Table 3.2 shows the 36 different conditions that were introduced to each brand. The experimental plan was designed such that all the three variables were changed. In total, 108 bottles were tested. For all the samples of bottles, bromate, turbidity, TDS, and total bacterial count (TBC) levels were tested. Among the 108 samples, 12 samples included additional parameters to be tested which were Bromide and TOC as shown in Table 3.2.

Table 3.2: Water bottles parameters and tests

No.	**pH**	**Temperature (°C)**	**Storage Time**	**Test**
1	6.5	20	1 day	Bromate, TDS, Turbidity, Bacteria
2			14 days	
3			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide
4		30	1 day	Bromate, TDS, Turbidity, Bacteria
5			14 days	
6			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide
7		40	1 day	Bromate, TDS, Turbidity, Bacteria
8			14 days	
9			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide
10		50	1 day	Bromate, TDS, Turbidity, Bacteria
11			14 days	
12			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide
13	7.5	20	1 day	Bromate, TDS, Turbidity, Bacteria
14			14 days	
15			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide
16		30	1 day	Bromate, TDS, Turbidity, Bacteria
17			14 days	
18			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide
19		40	1 day	Bromate, TDS, Turbidity, Bacteria
20			14 days	
21			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide
22		50	1 day	Bromate, TDS, Turbidity, Bacteria
23			14 days	
24			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide
25	8.5	20	1 day	Bromate, TDS, Turbidity, Bacteria
26			14 days	
27			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide
28		30	1 day	Bromate, TDS, Turbidity, Bacteria
29			14 days	
30			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide
31		40	1 day	Bromate, TDS, Turbidity, Bacteria
32			14 days	
33			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide
34		50	1 day	Bromate, TDS, Turbidity, Bacteria
35			14 days	
36			42 days	Bromate, TDS, TOC, Turbidity, Bacteria, Bromide

3.2.3 Analytical Methods

Several analytical techniques were used to measure the experimental parameters and conditions. Besides, different standards were followed for measuring each parameter as explained below.

3.2.3.1 pH

The pH of water samples was measured according to APHA 4500-H+ B standard method [48]. Thermo Orion 3 Star pH meter was the instrument. The electrodes were first removed from the storage solution, rinsed and dried using a soft tissue. The instrument was then calibrated using three buffer solutions. The buffer solutions pH levels were 4, 7 and 10 respectively. They were chosen to have almost the same temperature which was selected to be room temperature. After calibration, the probe was inserted in water samples where pH level was directly measured.

3.2.3.2 Total Bacterial Count (TBC)

TBC was measured according to APHA 9215 D standard method [48]. 1 mL of each sample was filtered through a 0.45µm sterile gridded membrane filter (Figure 3.2). Funnel was then rinsed with three portions of diluted water. The filter was placed on agar in petri dish. The dish was then placed in a box that contains moistened paper towels. It was incubated at 35 ± 0.5ºC for 48 hours. After the incubation period, the dish was removed and the total number of colonies formed in it was noted with a detection limit of Zero CFU/mL.

Figure 3.2: Sterilizing filter

3.2.3.3 Bromate

Bromate was measured according to USEPA 300.1 standard method [49]. 850 Professional Ion Chromatograph (IC) was used with a detection limit of 1ppb (see Figure 3.3). After IC was turned on, eluent solution, sodium carbonate, was then adjusted to flow at 0.7mL/min. The pressure was adjusted to a maximum of 15MPa. Equilibrium conditions were indicated after observing a stable base line in the IC. Reagent water, distilled water, was analyzed as a blank solution. Moving on, in order to achieve calibration, the following was done. First, three different concentrations of working standards, 5ppb, 10ppb, and 15ppb, were injected. The reason for injecting the standards was to bracket the expected analyte concentration. Next, a calibration curve was conducted by plotting peak height versus concentration. As samples were collected in PET bottles, no further collection procedure was required by the standard method. Finally, bromate was preserved by adding Ethylenediamine (EDA) preservation solution by which the final concentration was observed to be 50mg/L.

Figure 3.3: 850 Professional IC

In order to remove any particulates from the water samples, 0.45µm filter was used. Furthermore, to assure that the sample loop is properly flushed, sufficient samples were injected. In some cases where bromate was not detected, the results were confirmed by analyzing the sample via adding a known analyte concentration. Sample bromate concentration was computed by comparing its response to the standard curve.

3.2.3.4 Bromide

Bromide was measured according to the American Public Health Association (APHA) 4110B standard method [48]. 850 Professional Ion Chromatograph (IC) was also used with a detection limit of 1ppb (as shown in Figure 3.3). The approach was very similar to the one tested for bromate. Eluent solution, sodium carbonate, was adjusted to flow at 0.7mL/min. The pressure was adjusted to a maximum of 15MPa. Equilibrium conditions were indicated after observing a stable base line in the IC. Reagent water, distilled water, was analyzed as a blank solution. In order to achieve calibration, three different concentrations of working standards (10ppb, 50ppb, and 100ppb) were injected. The reason for injecting the standards was to bracket the expected analyte concentration. A calibration curve was then conducted by plotting peak height versus concentration. As samples were collected in PET bottles, no further collection procedure was required by the standard method. Unlike bromate, bromide does not require preservation.

In order to remove any particulates from the water samples, 0.45µm filter was used. Furthermore, to assure that the sample loop is properly flushed, sufficient samples were injected. In some cases, where bromate was not detected, the results were confirmed by analyzing the sample by adding a known analyte concentration. Sample Bromide concentration was computed by comparing its response to the standard curve.

3.2.3.5 Total Dissolved Solids (TDS)

TDS was measured according to the APHA 2540 C standard method [48]. At first, a clean evaporating dish was heated at a temperature of 180 ± 2°C for 1 hour in an oven. The dish was then stored in a desiccator (Figure 3.4) for the temperature to be balanced. Furthermore, it was measured before use. Volume of samples was selected with a range of dried residue between 2.5-200 mg for filtration purposes. The filtered sample was placed in the weighed evaporating dish and heated at a temperature of 180 ± 2°C for 1 hour in an oven. The detection limit for measuring TDS was 6ppm. In order to obtain the TDS amount in mg/L, the following equation was used:

$$TDS\ \left(\frac{mg}{L}\right) = \frac{(Weight\ of\ dried\ residue + dish, mg) - (Weight\ of\ dish)}{Sample\ Volume\ (mL)} \times 1000 \quad (1)$$

Figure 3.4: Desiccator

3.2.3.6 Turbidity

Turbidity was measured according to APHA 2130 B standard method [48]. Calibration solutions were already provided. However, in order to ensure the accuracy of the calibration scales, one standard was run in nephlemoter instrument with a detection limit of 0.10FTU (as shown in Figure 3.5). Samples were kept at room temperature before analysis. They were then poured in turbidity meter tube. The turbidity was directly measured from the instrument scale.

Figure 3.5: Nephlemoter and calibration solutions

3.2.3.7 Total Organic Carbon (TOC)

TOC was measured according to the APHA 5310 B standard method [48]. The method is called high-temperature combustion method. TOC analyzer was used to measure TOC with a detection limit of 100ppb (Figure 3.6). The optimum temperature for total carbon (TC) ranges between 800°C and 850°C; whereas, the optimum temperature for inorganic carbon (IC) is around 150°C. In order to run the program, a template was first created. Next, a location was created for storing analysis results. After that, the analyzer was calibrated using potassium hydrogen phthalate (TC) and anhydrous (IC) solutions. The solutions contain 1000 mg carbon/L. Calibration was verified by injecting a check standard. The instrument first measured TC followed by IC. It finally measured TOC by using the equation below:

$$TOC = TC - IC \tag{2}$$

Figure 3.6: TOC analyzer

3.2.4 Statistical Analysis

Determination coefficient (R^2) was used to study the suitability of regression models in predicting the bromate concentration based on each independent variable (pH, temperature, storage time, TDS, Bromide and TOC). Linear regression analysis was done to study the effect of changing different factors and parameters that might influence bromate formation in water. Microsoft Excel program was used to find the determination coefficient and to perform linear regression analysis. Both single and multiple linear regression analyses were used. Single linear regression was used to study the effect of only one independent variable on bromate formation (equation 3).

$$\boldsymbol{Bromate = ax + b} \tag{3}$$

a,b: coefficients

x: independent variables (temperature, storage time, pH, bromide, TDS and TOC)

Multiple linear regression analysis was done to study the effect of pH, temperature and storage time on bromate levels. Three multiple linear regression analyses were used for brands X, Y and Z. Multiple least-squares linear regression model was used with a 95% confidence level to observe which independent factor had the most significant effect on bromate formation in PET bottle water. Equation 4 shows the multiple least-squares linear regression model used.

$$\boldsymbol{Bromate = a_o + \ a_1 Temp + a_2 Time + a_3 pH} \tag{4}$$

a_o,a_1,$a_{2,}$ a_3: coefficients

3.2.5 Quality Control and Assurance

Standard methods were used in testing water quality parameters. In order to ensure quality control in analytical methods, bromate concentration for brand X was measured three times. The mean was calculated to be 1.023µg/L with the standard deviation to be 0.00577 which reflects that the data is concentrated around the mean. It also reflects that the methods are reproducible and the concentrations measured were reliable.

4. Results and Discussions

4.1 Formation of Bromate

Bromate was found in all the three brands (X, Y and Z) after 1 day storage time (as shown in Figure 4.1). The existence of bromate in brand X was expected as the treatment process used in purifying brand X water was ozonation. Bromide, which naturally exists in raw water, may have reacted to form bromate. Initial bromate concentration of brand X was found to be between 2.2µg/L and 2.4µg/L which was the highest among all brands. Brand Y claimed that its water is bromate-free; however, results of 1 day storage time proved the opposite. Brand Y did not undergo any treatment process for its water, yet its bromate concentration ranged between 0.99µg/L and 2.1µg/L. Similarly, brand Z water did not undergo any treatment process, yet bromate was found. There might have been some oxidizing agent present in the water. It could have influenced the formation of bromate. Bromate concentration at 1 day storage time for brand Z ranged between 2.0µg/L and 2.1µg/L which was the lowest among all brands.

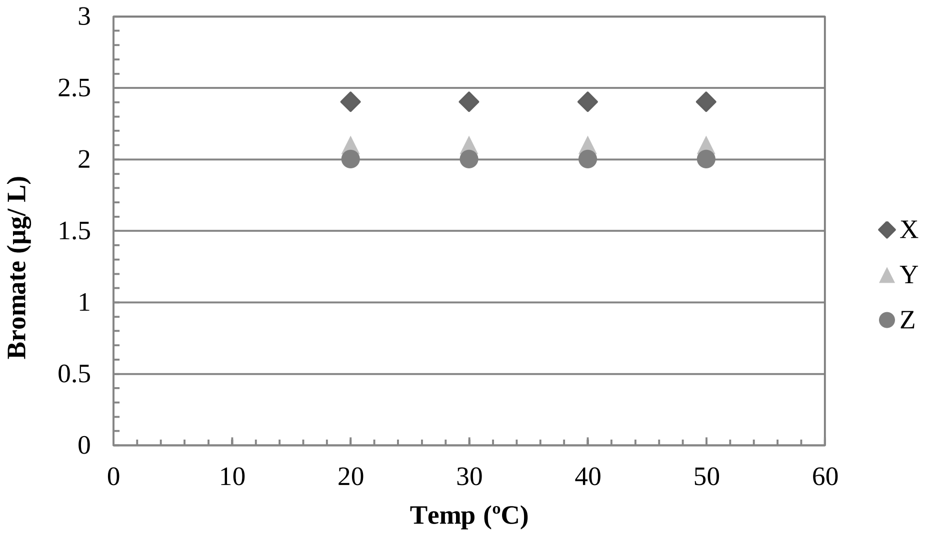

Figure 4.1: Bromate concentrations at 1 day and pH level of 7.5

The overall effect of each parameter is given by equations 5, 6 and 7 for brands X, Y and Z respectively. For all water brands, the temperature parameter was the least contributed parameter compared to storage time and pH level parameters.

The determination coefficients were calculated to be 0.37, 0.63 and 0.86 for brands X, Y, and Z respectively.

$$\boldsymbol{Bromate = -0.0057Temp - 0.0071Time + 0.1459pH + 3.6880} \tag{5}$$

$$\boldsymbol{Bromate = -0.0010Temp - 0.0126Time + 0.6505pH - 1.6156} \tag{6}$$

$$\boldsymbol{Bromate = -0.0016Temp - 0.1095Time - 1.2876pH + 26.5198} \tag{7}$$

4.2 Factors Affecting Bromate Formation

4.2.1 Temperature

In order to observe the effect of temperature on bromate formation, other factors, including pH and storage time, were controlled. At 1 day storage time and a pH of 6.5, the effect of temperature variation is reflected in Figure 4.2. Varying the temperature between 20ºC to 50ºC did not have an impact on bromate formation. Bromate concentration remained the same for all temperatures for each brand and the determination coefficient could not be calculated (refer to Table 4.1). Temperature coefficient was calculated to be zero for all brands as shown in Table 4.2. In other words, a change in temperature did not have any effect on bromate formation. These results contradict with some of the literature as Amy and Siddiqui concluded that increasing temperature helped in increasing bromate formation [26]. The literature justified the results to that faster reaction kinetics might have occurred which enhanced bromate formation.

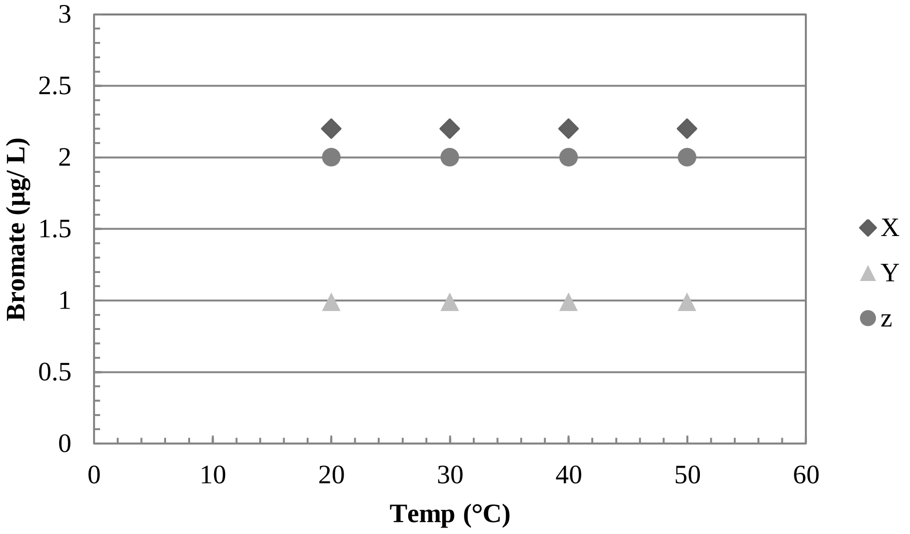

Figure 4.2: Bromate concentrations at 1 day and pH level of 6.5

Even with changes to pH levels of pH of 7.5 (Table A.2) and pH of 8.5 (Table A.3), similar results were observed. Bromate concentration remained the same regardless of the temperature it was exposed to. Temperature coefficients were calculated to be zero (Table 4.2). Bromate was not thermally driven by the changes in temperature between 20°C and 50°C at 1 day storage time regardless of the pH level. These results also contradicted the results concluded by Amy and Siddiqui [26]. The difference could be due to longer production date for some brands.

Table 4.1: Bromate determination coefficients with respect to temperature change

pH	Storage time (days)	Brand X R^2	Brand Y R^2	Brand Z R^2
6.5	1	NA	NA	NA
	14	0.3642	0.0456	NA
	42	0.0006	0.0609	NA
7.5	1	NA	NA	NA
	14	0.578	0.1415	NA
	42	0.9096	0.7885	NA
8.5	1	NA	NA	NA
	14	0.1976	0.6755	NA
	42	0.0004	0.4686	NA

Table 4.2: Bromate vs. temperature change equation

pH	Storage time (days)	Brand X Equation	Brand Y Equation	Brand Z Equation
6.5	1	y = 2.2	y = 0.99	y = 2
	14	y = 0.0082x + 1.478	y = -0.015x + 2.17	y = 0
	42	y = 0.0005x + 1.875	y = -0.0014x + 0.694	y = 0
7.5	1	y = 2.4	y = 2.1	y = 2
	14	y = -0.0123x + 2.623	y = 0.0022x + 2.158	y = 0
	42	y = -0.0224x + 3.054	y = -0.0152x + 2.337	y = 0
8.5	1	y = 2.4	y = 2.3	y = 2.1
	14	y = -0.0054x + 2.339	y = 0.0065x + 2.345	y = 0
	42	y = -0.0002x + 2.192	y = 0.0064x + 1.681	y = 0

Figure 4.3 shows the temperature effect on bromate formation at 14 days storage time and at a pH level of 6.5. The effect of temperature change on brand X was also not noticeable at 14 days storage time. The determination coefficient value for brand X was not significant at 0.36 (Table 4.1), and the temperature coefficient was 0.0082 (Table 4.2). While the temperature coefficient was very low, the positive sign indicated that temperature increase had an increasing effect on bromate formation. However, bromate concentration of brand Y reached its maximum at 30ºC unlike brand X which reached its maximum at 50ºC. The maximum bromate concentration (3µg/L) of brand Y might have resulted from an instrumental error. The determination coefficient value for bromate concentration change with temperature for brand Y was calculated to be 0.045604 (Table 4.1). Similar to brand X, the determination coefficient value for brand Y was very low implying that temperature does not have significant impact on bromate concentration.

The effect of temperature on bromate formation at 14 days storage time and at a pH level of 7.5 (Table A.11) was not visible for all brands. Determination coefficient of brand X was 0.578 (Table 4.1) which reflects a larger impact of temperature on bromate formation than those observed at similar conditions but with a pH level of 6.5 (0.36). Moreover, temperature coefficient of brand X was -0.0123 (Table 4.2) which reflects that increasing temperature caused a decrease in bromate formation. The bromate concentration of the same brand was not affected by the temperature as the determination coefficient was 0.1415 (Table 4.1).

A similar behavior was observed for bromate concentration at 14 days storage time and pH level of 8.5 (Tables A.12, A.15 and A.18). The effect of temperature was not considerable for brand X where the determination coefficient was calculated to be 0.1976 (Table 4.1). The determination coefficient of brand Y was 0.6755 (Table 4.1). However, the temperature coefficient of the same brand was 0.0065 (Table 4.2) suggesting that temperature effect on bromate formation was insignificant. All 42 days results showed that temperature had no significant impact on bromate formation. As concluded at 1 day storage time, bromate formation is not thermally driven by temperature changes from 20°C to 50°C.

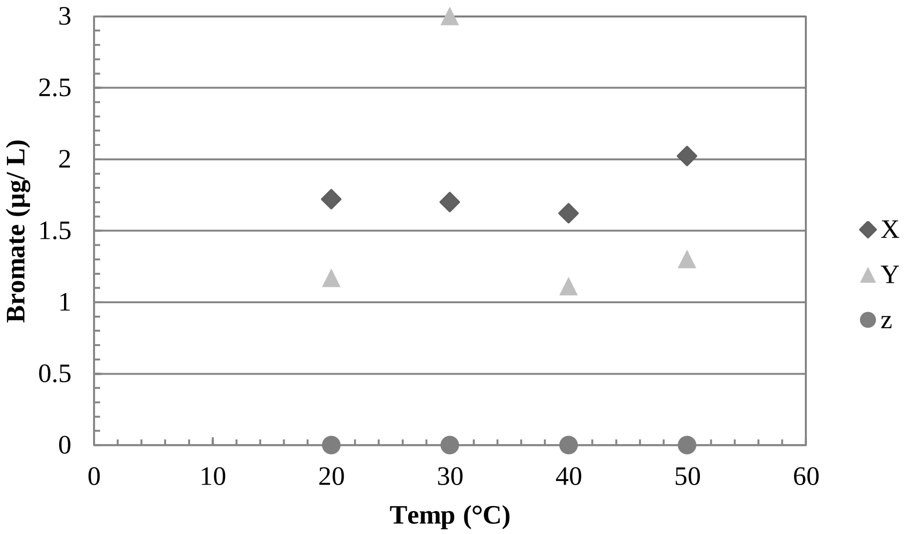

Figure 4.3: Bromate concentrations at 14 days and pH level of 6.5

Figure 4.4 reflects bromate concentrations at 42 days storage time and pH 6.5.Temperature effect of brand X on bromate formation was insignificant with a determination coefficient of 0.0006 (Table 4.1). At 20°C, its bromate level was observed to be 2.08µg/L where it decreased when temperature was increased to 30°C to 1.74µg/L. This result contradicted Amy and Siddiqui’s conclusion where bromate formation increased with temperature increase from 20°C to 30°C [26]. However, the results are in line with Krasner where increasing temperature from 13ºC to 23ºC reduced bromate [25]. Unlike brand X, bromate formation in brand Y increased when temperature was increased from 20°C to 30°C. These results are in line with Amy and Siddiqui’s findings [26]. The difference in results between brands X and Y may have occurred because of the difference in source water type [27]. Chemical reactions might have been enhanced for brand Y due to different amounts of acid and base added for each brand. Similar to previous results, bottled water of brand Z did not have any level of bromate at 42 days storage time.

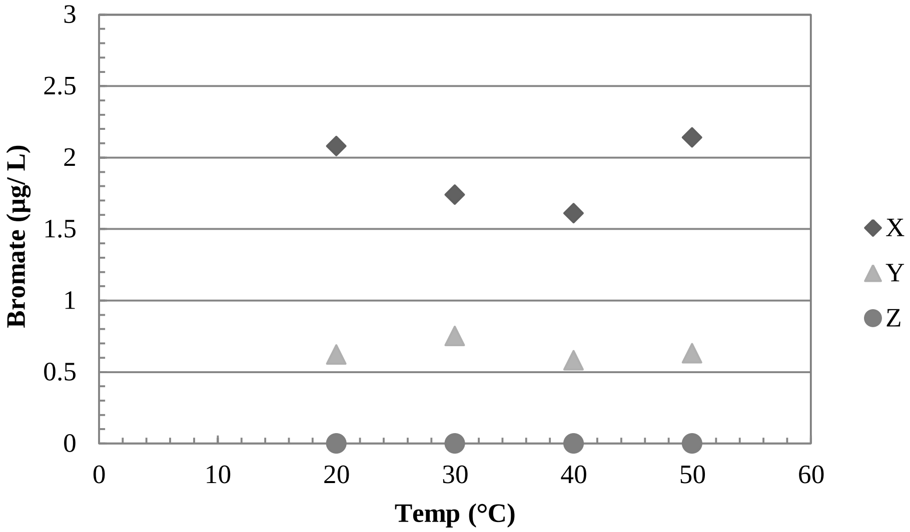

Figure 4.4: Bromate concentrations at 42 days and pH level of 6.5

Furthermore, bottles stored for 42 days at a pH level of 7.5 (Tables A.20, A.23 and A.26) were much more affected by the temperature changes compared to pH of 6.5 and 8.5. Determination coefficient of brand X was 0.9096 (Table 4.1) which indicated a linear relationship between bromate formation and temperature. However, bromate formation decreased with temperature increase with a temperature coefficient of -0.0224 (Table 4.2). Brand Y also had linear relationship between bromate formation and temperature with a determination coefficient of 0.7885 (Table 4.1). Brand Y temperature coefficient, -0.0152 (Table 4.2), indicated that temperature increase caused a decrease in bromate formation. A pH of 7.5 might had led to a more significant effect of temperature on bromate formation since this pH level is the closest to the original pH levels of the brands of 7.8 and 7.1 for brands X and Y respectively. The effect of adding acid or base might have affected the reactions of other pH levels 6.5 and 8.5. The effect of temperature change on bromate formation at 42 days and pH 8.5 was negligible for brands X and Y with determination coefficients -0.0002 and 0.0064 respectively.

The overall effect of temperature on bromate formation for all brands was insignificant as shown in equations 5, 6 and 7. However, brand X had the highest observed temperature effect on bromate formation where it had a coefficient value of -0.0057.

4.2.2 Storage Time

In order to observe the effect of storage time on bromate formation, other factors, such as temperature and pH, were controlled. Bromate concentrations at pH 6.5 and temperature of 20°C are reflected in Figure 4.5. Determination coefficient of brand X was 0.00118 (Table 4.4) which suggests a negligible effect of storage time on bromate formation. An explanation for this could be that brand X had the most recent production date compared to others. Brand Y had the highest bromate level at 14 days storage time regardless of the pH level and temperature. Determination coefficient of brand Y was 0.64128 (Table 4.3) which is much higher than that observed for brand X. Brand Y had a negative relationship between storage time and bromate formation with storage time coefficient of -0.0107 (Table 4.4). The older production date may have caused bromate to decrease. Brand Z had bromate only at 1 day storage time. Brand Z, which had the oldest production date, observed the highest impact of storage time on bromate formation with storage time coefficient of -0.041. Brand Z remained bromate free at 14 days storage time regardless of the pH and temperature. Bromate might have disappeared because of degradation that happened to brand Z. Water bottles were opened at the first day for pH adjustments; therefore, exposure to air and light may have caused a chemical reaction that caused the degradation in bromate formation for brand Z [50]. Similar to brands X and Y, increasing storage time caused a decrease in bromate concentrations for brand Z.

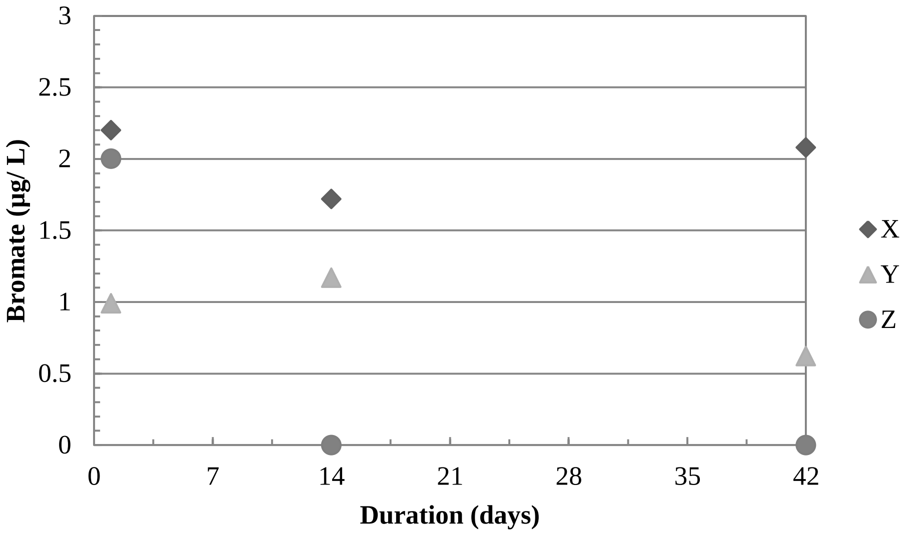

Figure 4.5: Bromate concentrations at 20ºC and pH level of 6.5

Table 4.3: Bromate determination coefficients with respect to storage time change

Temperature (°C)	pH	Brand X R^2	Brand Y R^2	Brand Z R^2
20	6.5	0.00118	0.64128	0.55353
	7.5	0.98959	0.04271	0.55353
	8.5	0.09624	0.73093	0.55353
30	6.5	0.48159	0.09043	0.55353
	7.5	0.00134	0.60897	0.55353
	8.5	0.92891	0.50487	0.55353
40	6.5	0.56822	0.74178	0.55353
	7.5	0.98424	0.7897	0.55353
	8.5	0.00014	0.63969	0.55353
50	6.5	0.01562	0.48943	0.55353
	7.5	0.48796	0.69624	0.55353
	8.5	0.28036	0.30387	0.55353

Table 4.4: Bromate vs. storage time change equation

Temperature (°C)	pH	Brand X Equation	Brand Y Equation	Brand Z Equation
20	6.5	$y = -0.0004x + 2.0078$	$y = -0.0107x + 1.1303$	$y = -0.041x + 1.4457$
	7.5	$y = 0.0067x + 2.3821$	$y = -0.0005x + 2.1353$	$y = -0.041x + 1.4457$
	8.5	$y = -0.0021x + 2.2994$	$y = -0.0134x + 2.4451$	$y = -0.0431x + 1.518$
30	6.5	$y = -0.0092x + 2.0549$	$y = -0.0177x + 1.9169$	$y = -0.041x + 1.4457$
	7.5	$y = 0.0003x + 2.2642$	$y = -0.0106x + 2.2475$	$y = -0.041x + 1.4457$
	8.5	$y = -0.0101x + 2.4553$	$y = -0.0117x + 2.4993$	$y = -0.0431x + 1.518$
40	6.5	$y = -0.0122x + 2.0409$	$y = -0.0114x + 1.1104$	$y = -0.041x + 1.4457$
	7.5	$y = -0.0083x + 2.3913$	$y = -0.0079x + 2.1742$	$y = -0.041x + 1.4457$
	8.5	$y = -0.0001x + 2.2586$	$y = -0.0142x + 2.4865$	$y = -0.0431x + 1.518$
50	6.5	$y = -0.0005x + 2.1304$	$y = -0.0112x + 1.1861$	$y = -0.041x + 1.4457$
	7.5	$y = -0.0076x + 2.2814$	$y = -0.015x + 2.2754$	$y = -0.041x + 1.4457$
	8.5	$y = -0.0046x + 2.2866$	$y = -0.0082x + 2.51$	$y = -0.0431x + 1.518$

The effect of storage time on bromate concentration for brand X at pH 6.5 and temperatures 30°C and 40°C was more significant than that observed at temperature 20°C. Determination coefficients of brand X at pH 6.5 and temperatures 30°C and 40°C were 0.482 and 0.568 respecitvely (Table 4.3). Storage time coefficients of brand X were -0.0092 and -0.0122 (Table 4.4) at temperatures 30°C and 40°C respectively. The effect of storage time on brand X, although higher than that observed at a temperature of 20°C, is still considered insignificant. Determination coefficeints of brand Y were 0.090 and 0.741 at pH 6.5 and temperatures of 30°C and 40°C respectively. The effect of storage time at temperature 30°C and pH 6.5 was insignificant for brand Y. Although a temperature of 40°C had a strong relation between storage time and bromate formation, the temperature coefficient was very low at -0.0114 (Table 4.4). At temperature 50°C and pH 6.5, all brands had a negligible effect of storage time on bromate formation with storage time coefficients of -0.0005, -0.0112 and -0.041 for brands X, Y and Z respectively (Table 4.4). As suggested earlier at pH 6.5 and temperature 20°C, the production date may have caused the negative relationship between storage time and bromate formation since the oldest production date (in brand Z) observed the highest effect; whereas, the newest production date observed the least effect on bromate formation.

At a pH level of 7.5 and temperature 20°C, bromate level of brand X increased with storage time (Figure 4.6). The determination coefficient for brand X was observed to be 0.99 which reflects a strong corelation between bromate formation and storage time. However, storage time effect on bromate formation was insignificant with storage time coefficient of 0.0067 (Table 4.3). Unlike brand X, determination coefficient value of brand Y was observed to be 0.0427 which also suggests that storage time effect is insignificant. Brand Z had only traces of bromate at 1 day storage time. The storage time effect on bromate formation was the same for brand Z at all pH levels and temperatures.

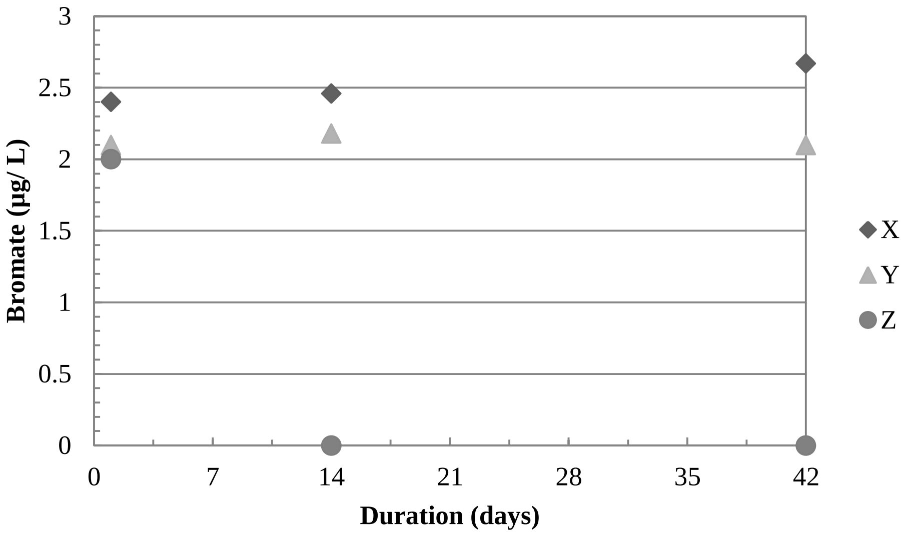

Figure 4.6: Bromate concentrations at 20°C and pH level of 7.5

At a pH level of 7.5 and temperatures of 30°C, 40°C and 50°C, determination coefficients of brand X were 0.00134, 0.98424 and 0.48796 respectively (Table 4.3). However, storage time coefficients of brand X were 0.0003, -0.0083 and -0.0076 respectively (Table 4.4). All storage time coefficients implied that increasing storage time had no significant effect on bromate formation regardless of the determination coefficients. Moreoever, determination coefficients of brand Y were calculated to be 0.60897, 0.7897 and 0.69624 at pH 7.5 and temperatures 30°C, 40°C and 50°C respectively. High coefficients values reflect a corelation between storage time and bromate formation. However, the corelation was not significant as storage time coefficients were calculated to be -0.0106, -0.0079 and -0.015 respectively. Generally, it was observed that brand Y had a stronger effect of storage time on bromate formation than brand X did due to older production date of brand Y.

At a pH level of 8.5 and temperature 20°C, the lowest level of bromate in brand X was observed at 14 days storage time unlike brand Y where the highest concentration was observed at the same storage time (Figure 4.11). The highest bromate level in brand X was observed at 1 day storage time. Determination coefficients were calculated to be 0.09624 and 0.73093 for brands X and Y respectively. Brand X had no correlation between storage time and bromate formation. However, brand Y observed a correlation between storage time and bromate formation, yet it was not significant with storage time coefficient of -0.0134 (Table 4.4). The effect of storage time on bromate formation for all brands at pH 8.5 and temperature 20°C was considered insignificant. However, similar to previous conclusions, production date might have influenced the effect of storage time on bromate formation.

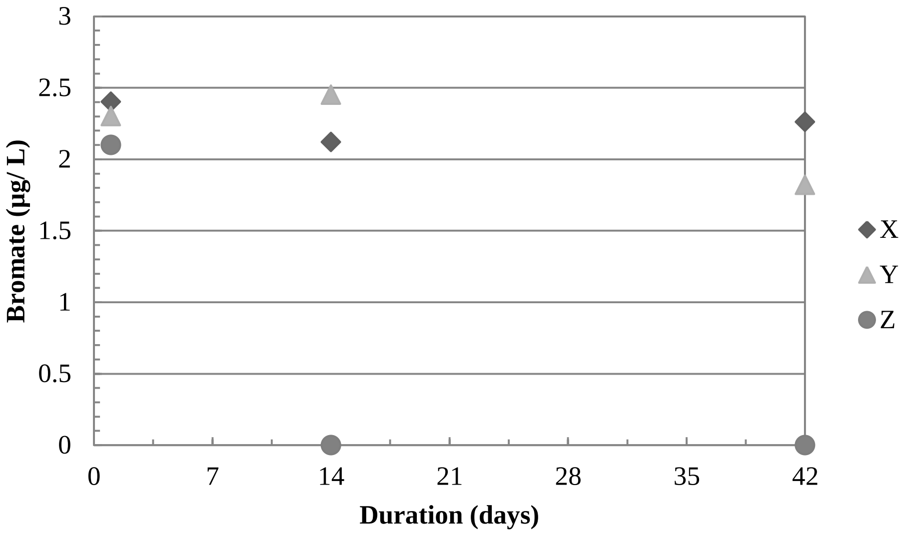

Figure 4.7: Bromate concentrations at 20°C and pH level of 8.5

The effect of storage time on brand X at a pH level of 8.5 was almost the same with exposure to various temperatures. For instance, at a pH level of 8.5 and temperatures 30°C, 40°C and 50°C, determination coefficients of brand X were 0.92891, 0.00014 and 0.28036 respectively (Table 4.3). Although the determination coefficient of brand X was high at temperature 30°C and pH 8.5, storage time coefficient was -0.0101 (Table 4.4) which reflects that the correlation is insignificant. Temperatures 40°C and 50°C determination coefficients indicated that there is no correlation between bromate formation and storage time. A similar observation was made for brand Y. The effect of storage time on brand Y at a pH level of 8.5 was similar with exposure to various temperatures.

Storage time of each brand prior to experimentation differed due to differences in the production dates of each of them. Based on equation 7, brand Z had the highest impact of storage time on bromate concentration with a coefficient value of -0.1095. As previously discussed, this may have resulted from brand Z having the oldest production date. Brand X; on the other hand, had the newest production date; therefore, the effect of storage time was not significant with a coefficient value of -0.0057 (equation 5). No previous studies were made to look at the effect of storage time on bromate formation after treatment is completed.

4.2.3 pH

The effect of pH on bromate formation was performed by controlling temperature and storage time. Figure 4.8 shows bromate concentrations for a 1 day storage time and a temperature of 20°C. Bromate levels of brand X increased from 2.2µg/L to 2.4µg/L with increasing pH level from 6.5 to 8.5. The determination coefficient value for pH was calculated to be 0.75 (Table 4.5). This indictated that changing pH from acidic to basic level in brand X has enhanced bromate formation. The coefficient of pH in brand X was calculated to be 0.1 indicating a positive linear relation to bromate formation. This might have been due to the increase in the ratio between hypobromite to hyporbromous acid, which if increased, increases the bromate formation [27]. A previous study conducted by Amy and Siddiqui concluded similar results where increasing pH level from 6 to 8.5 increased bromate formation in water [26]. Bromate levels in brand Y increased from 0.99µg/L to 2.1µg/L with a determination coefficient value of 0.86 (Table 4.5). Similar to brand X, increasing pH level in brand Y enhanced bromate formation. However, the effect of pH level on bromate formation was observed to be much higher for brand Y with a pH coefficient of 0.655 than it was for brand X with a pH coefficient of 0.1 (Table 4.6). Brand Z was the least affected by pH with a pH coefficient of 0.05 (Table 4.6).

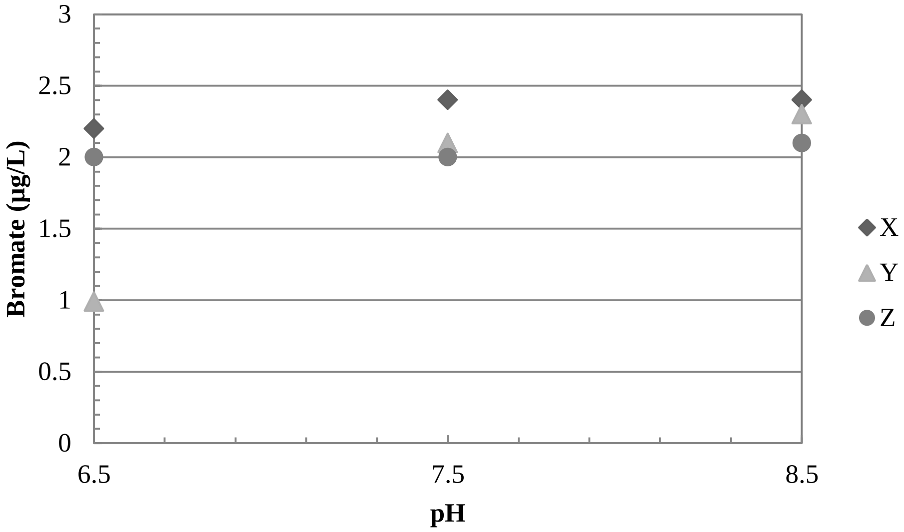

Figure 4.8: Bromate concentrations at 20°C and 1 day storage time

The effect of increasing pH level on bromate formation at 1 day storage time yielded similar results at all temperatures for all brands (Tables 4.5 and 4.6). Determination coefficients of brands X, Y and Z were exactly the same at 1 day storage time and different temperatures. This similarity occurred since bromate concentrations remained the same with temperature change. The difference occurring between brands may have resulted due to the variations of the amount of acid and base added. Since HCL and NaOH were added to adjust pH levels, bromate formation might have been affected.

Table 4.5: Bromate determination coefficients with respect to pH change

Temperature (°C)	Storage time (days)	Brand X R^2	Brand Y R^2	Brand Z R^2
20	1	0.75	0.8614	0.75
	14	0.2915	0.8998	NA
	42	0.0886	0.5824	NA
30	1	0.75	0.8614	0.75
	14	0.9974	0.3091	NA
	42	0.2018	0.8622	NA
40	1	0.75	0.8614	0.75
	14	0.446	0.9318	NA
	42	0.9812	0.75	NA
50	1	0.75	0.8614	0.75
	14	0.25	0.9397	NA
	42	0.0048	0.9698	NA

Table 4.6: Bromate vs. pH change equation

Temperature (°C)	Storage time (days)	Brand X Equation	Brand Y Equation	Brand Z Equation
20	1	y = 0.1x + 2.133	y = 0.655x + 0.487	y = 0.05x + 1.93
	14	y = 0.2x + 1.7	y = 0.64x + 0.6533	y = 0
	42	y = 0.09x + 2.157	y = 0.6x + 0.3133	y = 0
30	1	y = 0.1x + 2.133	y = 0.655x + 0.487	y = 0.05x + 1.93
	14	y = 0.34x + 1.37	y = -0.195x + 3.027	y = 0
	42	y = 0.135x + 1.76	y = 0.585x + 0.3	y = 0
40	1	y = 0.1x + 2.1333	y = 0.655x + 0.487	y = 0.05x + 1.93
	14	y = 0.215x + 1.543	y = 0.715x + 0.507	y = 0
	42	y = 0.355x + 1.283	y = 0.615x + 0.17	y = 0
50	1	y = 0.1x + 2.1333	y = 0.655x + 0.487	y = 0.05x + 1.93
	14	y = 0.015x + 1.99	y = 0.695x + 0.707	y = 0
	42	y = 0.005x + 2.093	y = 0.72x - 0.0167	y = 0

At 14 days storage time and a temperature of 20°C, the effect of pH on bromate formation is reflected in Figure 4.9. In brand X, bromate concentration reached its maximum of 2.46µg/L at a pH level of 7.5. The determination coefficient was calculated to be 0.29 (Table 4.5). The determination coefficient value reduced significantly as compared to the determination coefficient achieved with the same conditions of 1 day storage time which was 0.75 (Table 4.5). This reduction might have occurred due to longer storage time which might have reduced the added acid and base effect on bromate formation. However, pH coefficient for brand X at 14 days storage time was calculated to be 0.2 which is higher than that calculated at 1 day storage time 0.1 (Table 4.4). Bromate levels in brand Y increased with an increase in pH levels. The determination coefficient value calculated for brand Y was 0.90 (Table 4.5) which was quite similar to the determination coefficient value calculated for the same conditions at 1 day storage time 0.86. At 14 days and temperature 20°C, pH coefficient of brand Y was calculated to be 0.64. The effect of pH increase was higher for brand Y than for Brand X. This difference might have occurred due to the difference in water source between brands X and Y [27]. Determination coefficients of brand Z at 14 days and 42 days were calculated to be NA since bromate concentrations were zero at all temperatures.

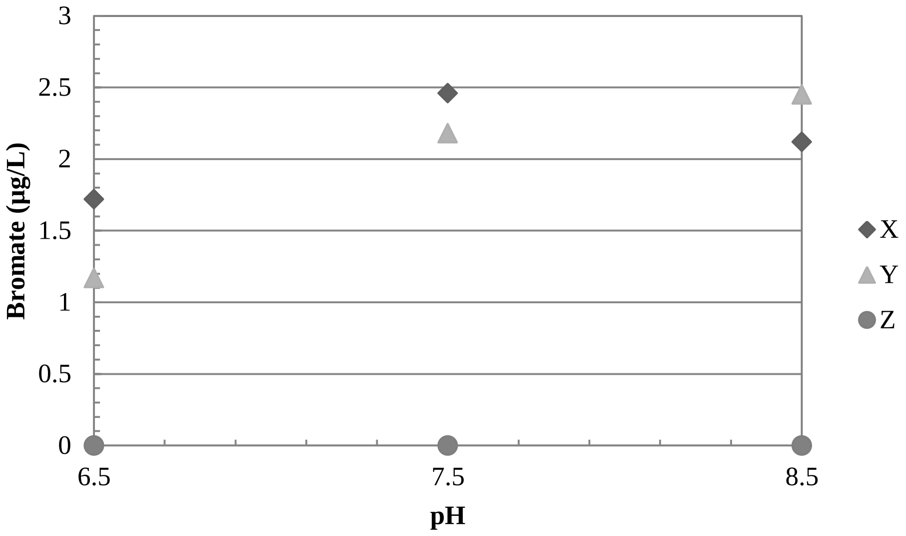

Figure 4.9: Bromate concentrations at 20°C and 14 days storage time

At 14 days storage time and a temperature of 30°C, bromate concentrations of brand X increased with an increase in pH levels with a determination coefficient value of 0.99 (Table 4.5). The high coefficient value reflected a strong correlation of pH level on bromate formation. pH coefficient of brand X was calculated to be 0.34 (Table 4.6) indicating that increasing pH level caused an increase in bromate formation. Nonetheless, Brand Y had a negative effect of increasing pH level on bromate formation with pH coefficient of -0.195 (Table 4.6). This may have been caused by an instrumental error at pH 6.5 where bromate concentration was at its highest level (3µg/L).

At 14 days storage time and a temperature of 40°C, determination coefficients of brands X and Y were 0.45 and 0.93 respectively. Brand Y had a stronger correlation between pH and bromate formation than brand X. Brand X had pH coefficient of 0.215 (Table 4.6). Brand Y had a pH coefficient of 0.715 (Table 4.6). Both brands had a positive relationship between bromate formation and pH increase. However, as noticed and discussed previously, the effect of pH increase on bromate formation is more significant for brand Y than brands X and Z.

At 14 days storage time and temperature 50°C, brand X increase in pH level had no significant impact on bromate formation with determination coefficient of 0.25. Bromate may have converted to other forms of by-products. Brand Y; on the other hand, had an increase in bromate formation associated with an increase in pH levels. The observed determination coefficient for brand Y was 0.94 (Table 4.5). pH coefficient of brand Y was calculated to be 0.9698. This points out that changing pH from an acidic (pH of 6.5) to a basic medium (pH of 8.5) enhances significantly bromate formation for brand Y.

At a 42 days storage time and temperature 20ºC (Figure 4.10), brands X and Y had their lowest bromate concentrations at a pH level of 6.5. Then, bromate reached its peak concentration at a pH level of 7.5 before decreasing at a pH level of 8.5. Brand X showed no linear relationship between an increase in pH levels and bromate formation where the observed determination coefficient value was 0.09. It indicated that pH change had no impact on bromate formation. Whereas, brand Y observed a correlation between bromate formation and an increase in pH levels with a determination coefficient of 0.58. pH coefficient of brand Y was 0.6. Similar to other results, brand Y observed a higher impact of increasing pH level on bromate formation due to difference in water source between brands X and Y.

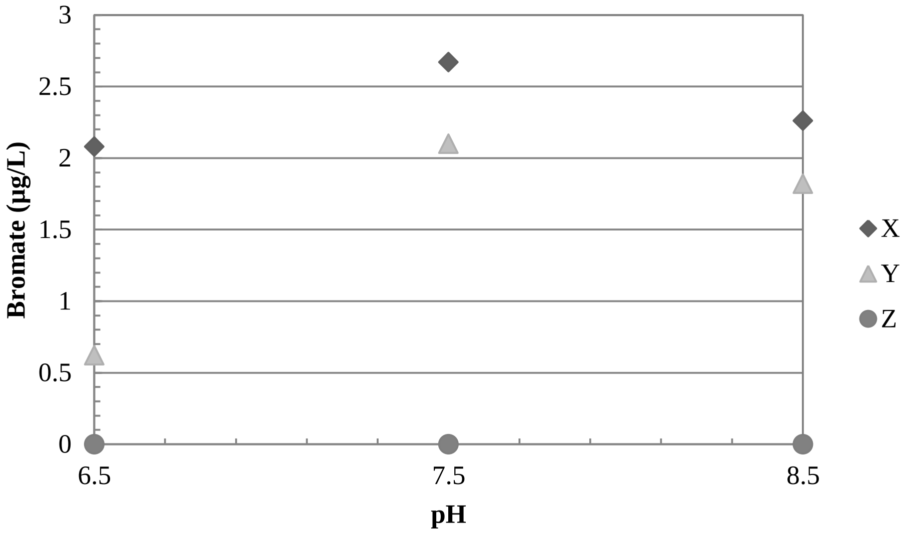

Figure 4.10: Bromate concentrations at 20°C and 42 days storage time

At 42 days storage time and temperatures of 30ºC, 40ºC and 50ºC, determination coefficients of brand X were 0.2018, 0.9812 and 0.0048. Only temperature 40ºC observed a correlation between pH and bromate formation; increasing pH caused an increase in bromate formation with pH coefficient of 0.355 (Table 4.6). At 42 days storage time and temperatures of 30ºC, 40ºC and 50ºC, determination coefficients of brand Y were 0.8622, 0.75 and 0.9698 (Table 4.5) respectively and pH coefficients were 0.585, 0.615 and 0.72 respectively (Table 4.6). The same conclusion was made as previously where brand Y observed the highest effect of pH increase on bromate formation than other brands. Most of the results of brand Y are in line with Amy and Siddiqui's results that increasing pH from 6 to 8.5, increased bromate formation in water [26]. The results were also in line with Krasner conclusions that indicate that reducing pH from 7.9 to 7 caused a reduction in bromate formation [25]. In addition, the results are in line with Aljundi results where increasing pH to 9 resulted in increasing bromate formation [51].

Overall, increasing pH level caused an increase in bromate formation in both brands X and Y. Brand Y observed the highest effect with a pH coefficient of 0.6506 (equation 6). Brand Z; on the other hand, observed a decrease in bromate formation with pH level increase with a coefficient of -1.2876 (equation 7). This decrease was observed as brand Z had no traces of bromate found at 14 days and 42 days storage time.

4.3 Water Quality Parameters Affecting Bromate Formation

4.3.1 Bromide

In order to study the effect of bromide on bromate formation, the concentration of bromide at 42 days storage time was observed. As mentioned previously, brand X undergoes ozonation disinfection process which converts bromide to bromate. Bromate concentrations against bromide are reflected in Figure 4.11 for brand X. Bromide effect on bromate formation was insignificant as the determination coefficient was calculated to be 0.0237. The very low determination coefficient indicated that no correlation could be observed between bromate formation and bromide concentrations. This might have resulted since bromide effect on bromate formation is mainly noticed during ozonation process [27]. The results contradicted the findings by Amy and Siddiqui's study where an increase in bromide concentration resulted in an increase in bromate formation [26].

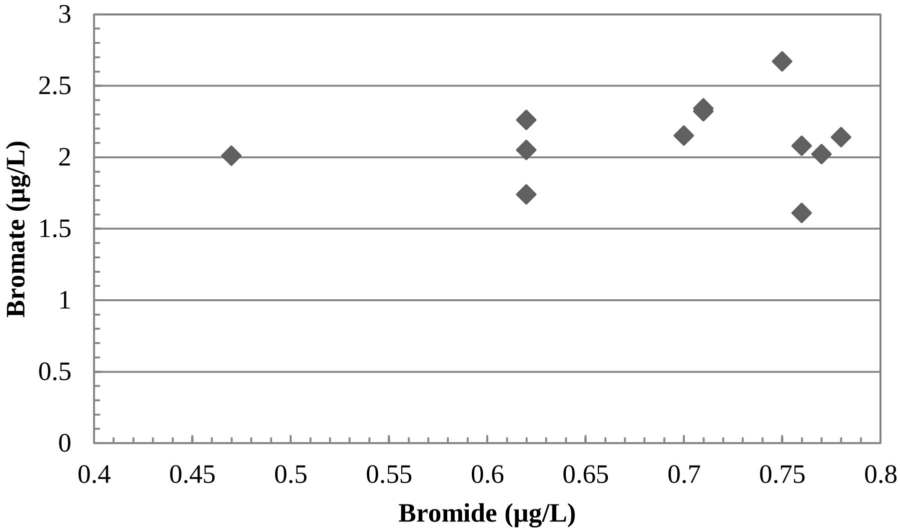

Figure 4.11: Brand X bromate concentrations with respect to bromide

Bromate concentrations of brand Ywith respect to bromide is shown in Figure 4.12. The determination coefficient was calculated to be 0.5678 which reflects a stronger linear effect of bromide on bromate formation as compared to brand X which had a low determination coefficient of 0.0237. Unlike brand X, increasing bromide concentration for Brand Y had a decreasing effect on bromate formation where bromide coefficient was calculated to be -3.751 (equation 8). Unlike brand X, brand Y did not go through any treatment process and hence bromide was not expected to have any increasing effect on bromate formation. Moreoever, brand Y had an older production date than brand X; therefore, the reaction of converting bromide to bromate may have already been completed. Bromide levels of brand Y did not enhance bromate formation. Since other factors were not controlled, any of these factors, such as pH, temperature and storage time, may have influenced bromide reactivity in forming bromate. HCL and NaOH might have reacted as oxidizing agents affecting bromide reactivity in influencing bromate formation. These results contradicted findings by Amy and Siddiqui where increasing bromide levels led to increases in bromate formation [26].

$$\boldsymbol{Bromate = -3.751 Bromide + 3.6085} \quad (8)$$

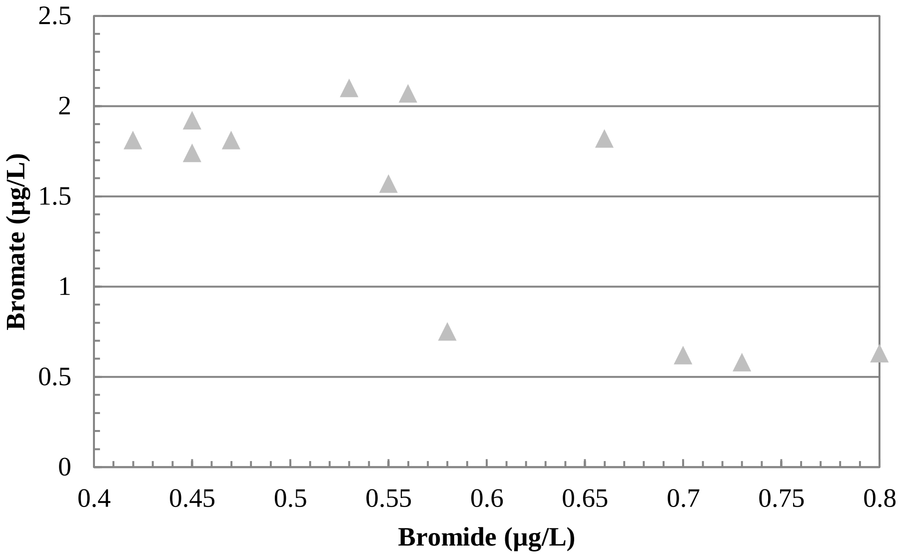

Figure 4.12: Bromate concentrations of brand Y with respect to bromide

Although brand Z contained bromide at 42 days storage time, yet no bromate was formed. No oxidizing agent was found to have enhanced bromide conversion to bromate. Therefore, no traces of bromate were detected for brand Z.

4.3.2 Total Dissolved Solids (TDS)

In order to study the effect of TDS on bromate formation, TDS concentrations were measured at all durations unlike bromide and TOC. TDS values for each brand differed significantly. Brand X TDS values ranged between 172mg/L and 180mg/L (Figure 4.13). Brand Y had the lowest TDS values where it ranged between 46mg/L and 56mg/L (Figure 4.14). Brand; Z on the other hand, had the highest observed TDS values that ranged between 370mg/L and 450mg/L (Figure 4.15). All brands had TDS levels that were below the unacceptable level of TDS in drinking water which is >1200mg/L [52].

Bromate concentrations of brand X with respect to TDS are reflected in Figure 4.13. The decrease in TDS level was due to changes in storage time between 14 days and 42 days. The effect of TDS on bromate formation for brand X was not significant since the observed determination coefficient was a negligible 0.0298. Both coefficients were very small which suggests that TDS did not have an impact on bromate formation regardless of the temperature, pH level and storage time.

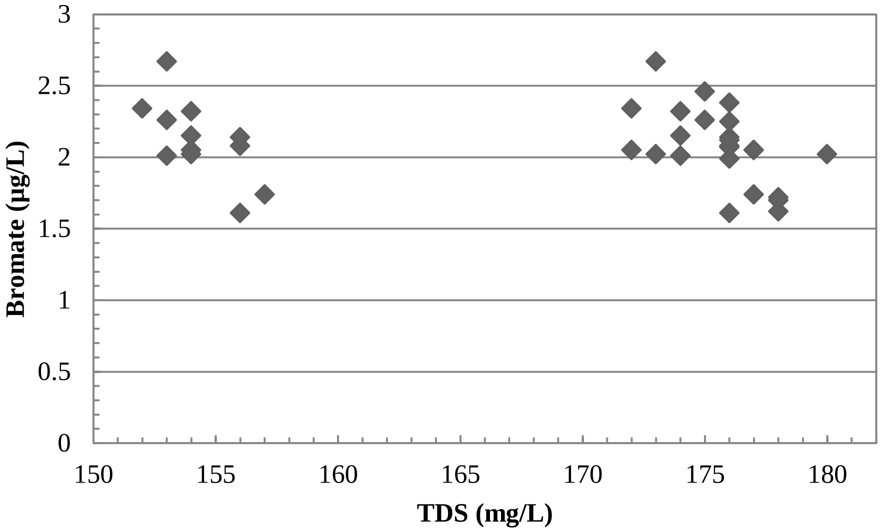

Figure 4.13: Bromate concentrations of brand X with respect to TDS change

Bromate concentrations of brand Y with respect to TDS are reflected in Figure 4.14. Determination coefficient of brand Y was 0.1795 which is low and reflects that no correlation exists between TDS and bromate formation. The effect of TDS on bromate formation for both brands X and Y seems to be negligible. However, there are no past studies that researched the relation between TDS and bromate formation in water.

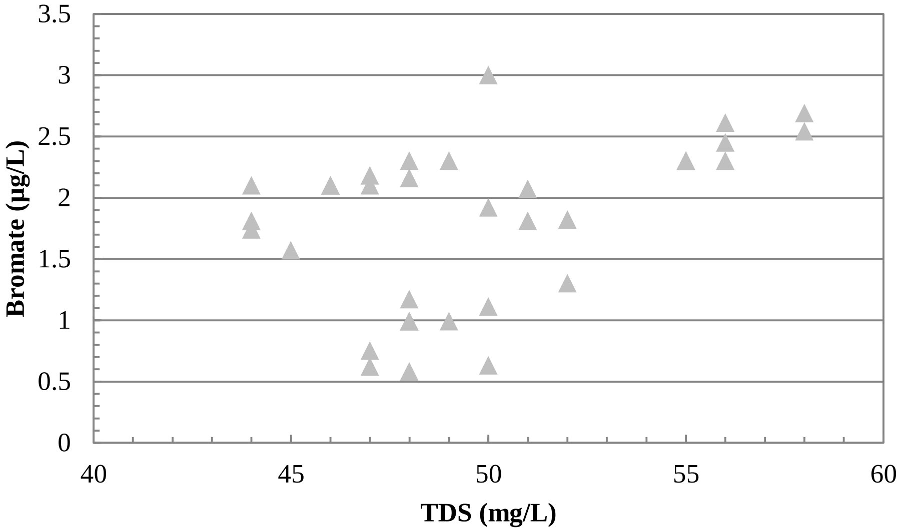

Figure 4.14: Brand Y bromate concentrations with respect to TDS change

High TDS levels of brand Z helped in adding a distinctive flavor to it. Brand Z bromate concentrations with respect to TDS change are reflected in Figure 4.15. Brand Z, which had the highest TDS levels, observed the lowest effect of TDS on bromate formation. Determination coefficient of brand Z was 0.1107 which reflects that there is no correlation between TDS and bromate formation for brand Z as well. Therefore, it may be easily concluded that TDS levels do not affect bromate formation in water.

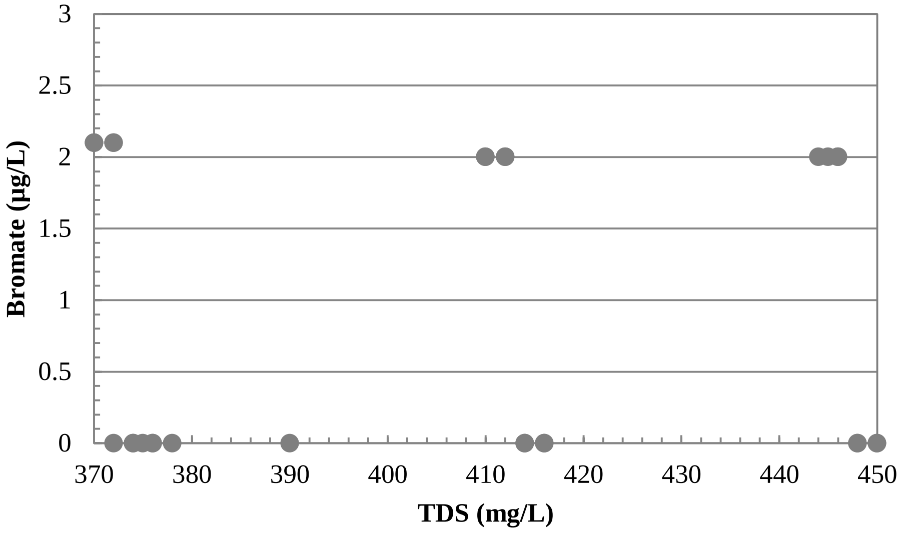

Figure 4.15: Brand Z bromate concentrations with respect to TDS change

4.3.3 Total Organic Carbon (TOC)

TOC was used as an indicator for organic material. The effect of TOC as a water quality parameter on bromate formation was investigated at 42 days storage time. Brand Y had the lowest TOC concentrations ranging from 0.19mg/L to 0.24mg/L as compared to other brands (Figure 4.17). Brand Z; on the other hand, had the highest observed TOC concentrations that range from 0.42mg/L to 0.63mg/L.

For Brand X, bromate and TOC concentrations are reflected in Figure 4.16. The determination coefficient was calculated to be 0.0176. The result is not significant as the determination coefficient showed no correlation between the two variables. A study conducted by Tanyan shows that TOC affects ozone demand, and in turn affects bromate formation [27]. However, the study was only limited to the effect of TOC on bromate formation during ozonation treatment. Since the tested bottles were after ozonation disinfection process, the effect on bromate formation could not be observed. Miltner reports that ozone to TOC ratio must reach 1 for bromate to be detected. Since ozone was not found at 42 days storage time, TOC was not expected to have an effect on bromate formation [28].

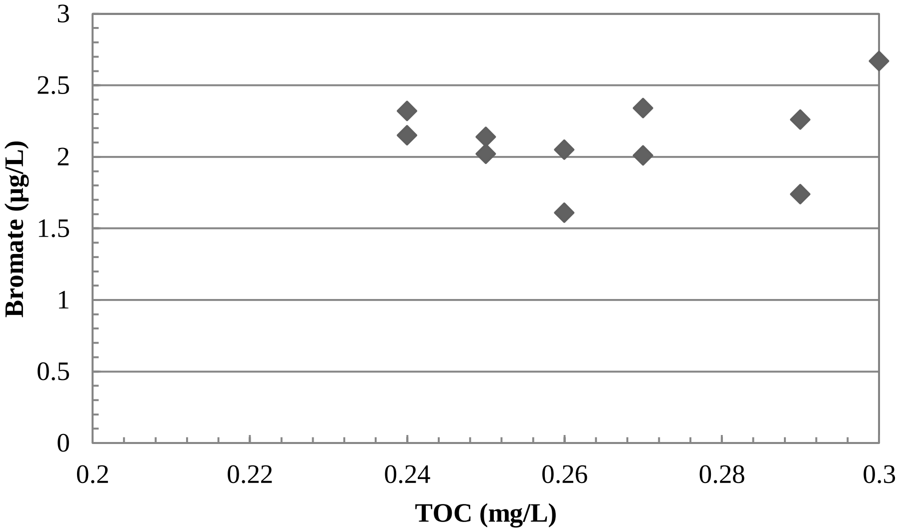

Figure 4.16: Brand X bromate concentrations with respect to TOC change

Although Brand Y (Figure 4.17) had the lowest TOC concentrations among all brands, its effect on bromate formation was observed to be greater than that of brand X. Determination coefficient for Brand Y was 0.1179; whereas, brand X determination coefficient was 0.0176. However, brand Y also reflected that there is no correlation between TOC and bromate formation. Ozone is one of the most influencing materials needed to enhance TOC effect on bromate formation [27] and [28]. Since brand Y did not undergo any ozonation process, the effect of TOC on bromate formation was not observed.

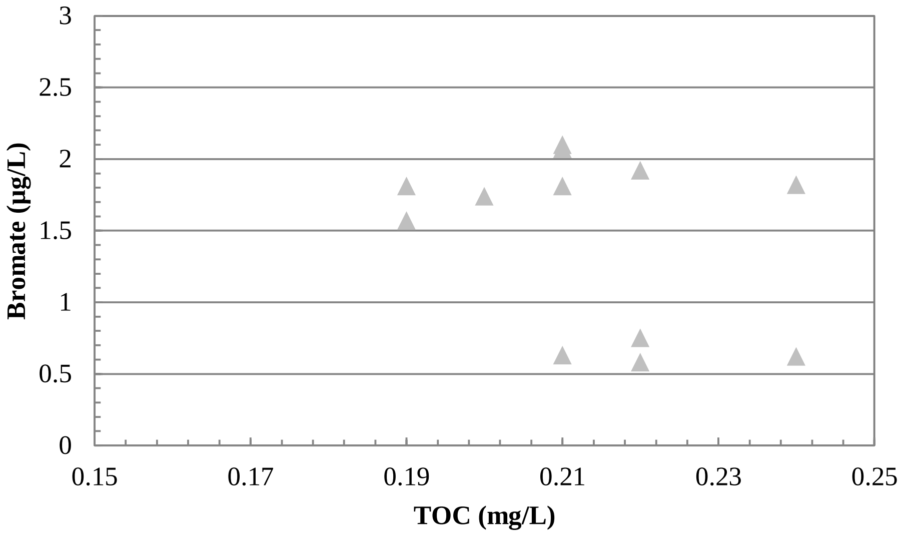

Figure 4.17: Brand Y bromate concentrations with respect to TOC change

As stated previously, brand Z contained no bromate concentrations under all 42 days storage time conditions, even when exposed to different pH levels and temperatures. Unlike other brands, the effect of TOC on bromate could not be established for brand Z. The lack of materials, such as ozone, restricted the effect of TOC on bromate formation for brand Z.

4.3.4 Other Parameters

Other parameters including turbidity and TBC were measured at all storage times. Regardless of the temperature, storage time and pH levels, water bottles were exposed to, turbidity and TBC were not found. Therefore, the effect of these parameters on bromate formation could not be investigated.

4.4 Health Implications of Bromate Formation

The MCL of bromate in drinking water is 10µg/L according to several organizations including the WHO and the EPA. However, European Commission has set a MCL of 3µg/L for natural mineral water treated by ozonation [23]. If bromate was found reaching MCL, it may cause lifetime cancer risk as mentioned previously. Regardless of the conditions water bottles were exposed to, bromate levels were found to be below the MCL level for the tested local, regional and international brands. Therefore, all tested brands could be considered safe in terms of bromate formation. The highest bromate value of brand X was 3µg/L which is the MCL allowed by European

Commission. To avoid exceeding the MCL set by European Commission, bromide could be removed using ion exchange or membrane filtration to restrict formation of bromate [53].

5. Conclusions and Recommendations

5.1 Conclusions

The fact of bromate being found in drinking water supplied in the UAE is of a concern to the public since bromate is classified as a possible carcinogen. Bromate formation in drinking water bottles was studied while exposed to various temperatures, storage times and pH levels. Regardless of the conditions that water bottles were exposed to, all bromate levels were found to be below MCL. Therefore, all tested brands could be considered safe in terms of bromate formation into the water. Brands X and Y contained bromate at all storage time; however, brand Z only had bromate at 1 day storage time. Storage time effect on bromate formation was insignificant with less than 1% effect. Bromate formation was found not to be thermally driven by changes in temperature. pH level; however, had the highest impact on bromate formation as compared to other tested parameters (temperature and storage time). Increasing pH level caused an increase in bromate formation in brands X and Y where basic pH is more preferred in bromate formation. Brand Z; on the other hand, observed a decrease in bromate formation with pH level increase.

The effect of water quality parameters was investigated. All tested water parameters including Bromide, TDS, TOC, TBC and Turbidity showed no correlation between each other and bromate formation for all tested brands. In some conditions, brand X bromate level was found to reach MCL set by European Commission, which is 3µg/L for natural mineral water treated by ozonation. Therefore, removal of bromide is suggested using ion exchange or membrane filtration to restrict formation of bromate.

5.2 Recommendations

The effect of bromide could have been observed better if studied at all storage times rather than only at 42 days storage time. In addition, it is recommended to study the possibility of bromate formation with reused PET water bottles since it happens significantly. Other parameter effect on bromate formation could be reflected by exposing PET bottles to direct sunlight and studying its effect since numerous bottles are exposed to sunlight during transportation in the UAE. Further studies could study other types of water, such as desalinated water where the effect of bromate formation might be more significant. Furthermore, in order to study the direct effect of PET bottles, water initial bromate levels before being bottled could be observed. Since tested water bottles were opened at the beginning of the test to adjust the pH level, future studies could be conducted with pH adjustments being done after storage of the water bottles.

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Appendix

Additional Tables for the Experimental Data

Table A.1: Brand X 1 day, pH 6.5 results

1 day – Brand X					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
6.5	20°C	Total Dissolved Solids	APHA 2540 C	176	mg/ L
		Bromate	USEPA 300.1	2.2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	177	mg/ L
		Bromate	USEPA 300.1	2.2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	176	mg/ L
		Bromate	USEPA 300.1	2.2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	176	mg/ L
		Bromate	USEPA 300.1	2.2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.2: Brand X 1 day, pH 7.5 results

1 day – Brand X					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
7.5	20°C	Total Dissolved Solids	APHA 2540 C	173	mg/ L
		Bromate	USEPA 300.1	2.4	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	172	mg/ L
		Bromate	USEPA 300.1	2.4	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	172	mg/ L
		Bromate	USEPA 300.1	2.4	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	173	mg/ L
		Bromate	USEPA 300.1	2.4	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.3: Brand X 1 day, pH 8.5 results

1 day – Brand X					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
8.5	20°C	Total Dissolved Solids	APHA 2540 C	175	mg/ L
		Bromate	USEPA 300.1	2.4	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	174	mg/ L
		Bromate	USEPA 300.1	2.4	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	174	mg/ L
		Bromate	USEPA 300.1	2.4	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	174	mg/ L
		Bromate	USEPA 300.1	2.4	µg/ L
		Turbidity	APHA 2130 B	175	NTU
		Total Bacterial Count	APHA 9215 D	2.4	CFU/ ml

Table A.4: Brand Y 1 day, pH 6.5 results

1 day - Brand Y					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
6.5	20°C	Total Dissolved Solids	APHA 2540 C	48	mg/ L
		Bromate	USEPA 300.1	0.99	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	49	mg/ L
		Bromate	USEPA 300.1	0.99	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	48	mg/ L
		Bromate	USEPA 300.1	0.99	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	48	mg/ L
		Bromate	USEPA 300.1	0.99	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.5: Brand Y 1 day, pH 7.5 results

1 day - Brand Y					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
7.5	20°C	Total Dissolved Solids	APHA 2540 C	47	mg/ L
		Bromate	USEPA 300.1	2.1	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	46	mg/ L
		Bromate	USEPA 300.1	2.1	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	46	mg/ L
		Bromate	USEPA 300.1	2.1	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	46	mg/ L
		Bromate	USEPA 300.1	2.1	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.6: Brand Y 1 day, pH 8.5 results

1 day - Brand Y					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
8.5	20°C	Total Dissolved Solids	APHA 2540 C	56	mg/ L
		Bromate	USEPA 300.1	2.3	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	55	mg/ L
		Bromate	USEPA 300.1	2.3	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	55	mg/ L
		Bromate	USEPA 300.1	2.3	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	55	mg/ L
		Bromate	USEPA 300.1	2.3	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.7: Brand Z 1 day, pH 6.5 results

1 day - Brand Z					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
6.5	20°C	Total Dissolved Solids	APHA 2540 C	446	mg/ L
		Bromate	USEPA 300.1	2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	445	mg/ L
		Bromate	USEPA 300.1	2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	444	mg/ L
		Bromate	USEPA 300.1	2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	446	mg/ L
		Bromate	USEPA 300.1	2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.8: Brand Z 1 day, pH 7.5 results

1 day - Brand Z					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
7.5	20°C	Total Dissolved Solids	APHA 2540 C	410	mg/ L
		Bromate	USEPA 300.1	2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	412	mg/ L
		Bromate	USEPA 300.1	2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	410	mg/ L
		Bromate	USEPA 300.1	2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	412	mg/ L
		Bromate	USEPA 300.1	2	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.9: Brand Z 1 day, pH 8.5 results

1 day - Brand Z					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
8.5	20°C	Total Dissolved Solids	APHA 2540 C	372	mg/ L
		Bromate	USEPA 300.1	2.1	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	370	mg/ L
		Bromate	USEPA 300.1	2.1	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	372	mg/ L
		Bromate	USEPA 300.1	2.1	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	370	mg/ L
		Bromate	USEPA 300.1	2.1	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.10: Brand X 14 days, pH 6.5 results

14 days– Brand X					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
6.5	20°C	Total Dissolved Solids	APHA 2540 C	178	mg/ L
		Bromate	USEPA 300.1	1.72	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	178	mg/ L
		Bromate	USEPA 300.1	1.7	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	178	mg/ L
		Bromate	USEPA 300.1	1.62	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	180	mg/ L
		Bromate	USEPA 300.1	2.02	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.11: Brand X 14 days, pH 7.5 results

14 days– Brand X					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
7.5	20°C	Total Dissolved Solids	APHA 2540 C	175	mg/ L
		Bromate	USEPA 300.1	2.46	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	176	mg/ L
		Bromate	USEPA 300.1	2.07	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	176	mg/ L
		Bromate	USEPA 300.1	2.25	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	176	mg/ L
		Bromate	USEPA 300.1	1.99	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.12: Brand X 14 days, pH 8.5 results

14 days– Brand X					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
8.5	20°C	Total Dissolved Solids	APHA 2540 C	176	mg/ L
		Bromate	USEPA 300.1	2.12	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	176	mg/ L
		Bromate	USEPA 300.1	2.38	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	177	mg/ L
		Bromate	USEPA 300.1	2.05	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	177	mg/ L
		Bromate	USEPA 300.1	2.05	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A13: Brand Y 14 days, pH 6.5 results

14 days– Brand Y					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
6.5	20°C	Total Dissolved Solids	APHA 2540 C	48	mg/ L
		Bromate	USEPA 300.1	1.17	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	50	mg/ L
		Bromate	USEPA 300.1	3	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	50	mg/ L
		Bromate	USEPA 300.1	1.11	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	52	mg/ L
		Bromate	USEPA 300.1	1.3	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.14: Brand Y 14 days, pH 7.5 results

14 days– Brand Y					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
7.5	20°C	Total Dissolved Solids	APHA 2540 C	47	mg/ L
		Bromate	USEPA 300.1	2.18	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	48	mg/ L
		Bromate	USEPA 300.1	2.3	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	48	mg/ L
		Bromate	USEPA 300.1	2.16	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	49	mg/ L
		Bromate	USEPA 300.1	2.3	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.15: Brand Y 14 days, pH 8.5 results

14 days– Brand Y					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
8.5	20°C	Total Dissolved Solids	APHA 2540 C	56	mg/ L
		Bromate	USEPA 300.1	2.45	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	56	mg/ L
		Bromate	USEPA 300.1	2.61	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	58	mg/ L
		Bromate	USEPA 300.1	2.54	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	58	mg/ L
		Bromate	USEPA 300.1	2.69	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	56	CFU/ ml

Table A.16: Brand Z 14 days, pH 6.5 results

14 days– Brand Z					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
6.5	20°C	Total Dissolved Solids	APHA 2540 C	448	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	448	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	450	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	450	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.17: Brand Z 14 days, pH 7.5 results

14 days– Brand Z					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
7.5	20°C	Total Dissolved Solids	APHA 2540 C	414	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	414	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	416	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	416	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.18: Brand Z 14 days, pH 8.5 results

14 days– Brand Z					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
8.5	20°C	Total Dissolved Solids	APHA 2540 C	374	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	374	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	376	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	376	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.19: Brand X 42 days, pH 6.5 results

42 days – Brand X					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
6.5	20°C	Total Dissolved Solids	APHA 2540 C	156	mg/ L
		Bromate	USEPA 300.1	2.08	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.32	mg/L
		Bromide	APHA 4110B	0.76	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	157	mg/ L
		Bromate	USEPA 300.1	1.74	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.29	mg/L
		Bromide	APHA 4110B	0.62	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	156	mg/ L
		Bromate	USEPA 300.1	1.61	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.26	mg/L
		Bromide	APHA 4110B	0.76	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	156	mg/ L
		Bromate	USEPA 300.1	2.14	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.25	mg/L
		Bromide	APHA 4110B	0.78	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.20: Brand X 42 days, pH 7.5 results

42 days – Brand X					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
7.5	20°C	Total Dissolved Solids	APHA 2540 C	153	mg/ L
		Bromate	USEPA 300.1	2.67	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.3	mg/L
		Bromide	APHA 4110B	0.75	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	152	mg/ L
		Bromate	USEPA 300.1	2.34	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.27	mg/L
		Bromide	APHA 4110B	0.71	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	154	mg/ L
		Bromate	USEPA 300.1	2.05	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.26	mg/L
		Bromide	APHA 4110B	0.62	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	154	mg/ L
		Bromate	USEPA 300.1	2.02	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.25	mg/L
		Bromide	APHA 4110B	0.77	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.21: Brand X 42 days, pH 8.5 results

42 days – Brand X					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
8.5	20°C	Total Dissolved Solids	APHA 2540 C	153	mg/ L
		Bromate	USEPA 300.1	2.26	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.29	mg/L
		Bromide	APHA 4110B	0.62	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	153	mg/ L
		Bromate	USEPA 300.1	2.01	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.27	mg/L
		Bromide	APHA 4110B	0.47	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	154	mg/ L
		Bromate	USEPA 300.1	2.32	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.24	mg/L
		Bromide	APHA 4110B	0.71	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	154	mg/ L
		Bromate	USEPA 300.1	2.15	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.24	mg/L
		Bromide	APHA 4110B	0.7	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.22: Brand Y 42 days, pH 6.5 results

42 days – Brand Y					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
6.5	20°C	Total Dissolved Solids	APHA 2540 C	47	mg/ L
		Bromate	USEPA 300.1	0.62	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.24	mg/L
		Bromide	APHA 4110B	0.7	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	47	mg/ L
		Bromate	USEPA 300.1	0.75	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.22	mg/L
		Bromide	APHA 4110B	0.58	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	48	mg/ L
		Bromate	USEPA 300.1	0.58	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.22	mg/L
		Bromide	APHA 4110B	0.73	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	50	mg/ L
		Bromate	USEPA 300.1	0.63	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.21	mg/L
		Bromide	APHA 4110B	0.8	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.23: Brand Y 42 days, pH 7.5 results

42 days – Brand Y					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
7.5	20°C	Total Dissolved Solids	APHA 2540 C	44	mg/ L
		Bromate	USEPA 300.1	2.1	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.21	mg/L
		Bromide	APHA 4110B	0.53	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	44	mg/ L
		Bromate	USEPA 300.1	1.74	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	<0.20	mg/L
		Bromide	APHA 4110B	0.45	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	44	mg/ L
		Bromate	USEPA 300.1	1.81	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	<0.20	mg/L
		Bromide	APHA 4110B	0.47	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	45	mg/ L
		Bromate	USEPA 300.1	1.57	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	<0.20	mg/L
		Bromide	APHA 4110B	0.55	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.24: Brand Y 42 days, pH 8.5 results

42 days – Brand Y					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
8.5	20°C	Total Dissolved Solids	APHA 2540 C	52	mg/ L
		Bromate	USEPA 300.1	1.82	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.24	mg/L
		Bromide	APHA 4110B	0.66	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	50	mg/ L
		Bromate	USEPA 300.1	1.92	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.22	mg/L
		Bromide	APHA 4110B	0.45	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	51	mg/ L
		Bromate	USEPA 300.1	1.81	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.21	mg/L
		Bromide	APHA 4110B	0.42	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	51	mg/ L
		Bromate	USEPA 300.1	2.07	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.21	mg/L
		Bromide	APHA 4110B	0.56	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.25: Brand Z 42 days, pH 6.5 results

42 days – Brand Z					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
6.5	20°C	Total Dissolved Solids	APHA 2540 C	378	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.59	mg/L
		Bromide	APHA 4110B	0.55	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	375	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.5	mg/L
		Bromide	APHA 4110B	0.55	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	372	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.48	mg/L
		Bromide	APHA 4110B	0.56	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	390	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.46	mg/L
		Bromide	APHA 4110B	0.56	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.26: Brand Z 42 days, pH 7.5 results

42 days – Brand Z					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
7.5	20°C	Total Dissolved Solids	APHA 2540 C	333	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.6	mg/L
		Bromide	APHA 4110B	0.61	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	342	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.48	mg/L
		Bromide	APHA 4110B	0.58	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	328	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.46	mg/L
		Bromide	APHA 4110B	0.59	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	300	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.46	mg/L
		Bromide	APHA 4110B	0.6	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.27: Brand Z 42 days, pH 8.5 results

42 days – Brand Z					
pH	**Temp**	**Test**	**Method**	**Results**	**Unit**
8.5	20°C	Total Dissolved Solids	APHA 2540 C	314	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.63	mg/L
		Bromide	APHA 4110B	0.6	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	30°C	Total Dissolved Solids	APHA 2540 C	306	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.46	mg/L
		Bromide	APHA 4110B	0.56	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	40°C	Total Dissolved Solids	APHA 2540 C	306	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.44	mg/L
		Bromide	APHA 4110B	0.55	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml
	50°C	Total Dissolved Solids	APHA 2540 C	320	mg/ L
		Bromate	USEPA 300.1	Nil	µg/ L
		Turbidity	APHA 2130 B	0	NTU
		TOC	APHA 5310B	0.42	mg/L
		Bromide	APHA 4110B	0.56	µg/ L
		Total Bacterial Count	APHA 9215 D	ND	CFU/ ml

Table A.28: Brand X Bromate behavior (Reference: temperature 20°C and pH 6.5)

Brand X - Bromate (µg/L)					
Temperature pH	20	30	40	50	Storage Time
6.5	=	=	=	=	1 Day
	-	-	-	-	14 Days
	-	-	-	-	42 Days
7.5	+	+	+	+	1 Day
	+	-	+	-	14 Days
	+	+	-	-	42 Days
8.5	+	+	+	+	1 Day
	-	+	-	-	14 Days
	+	-	+	-	42 Days

Table A.29: Brand Y Bromate behavior (Reference: temperature 20°C and pH 6.5)

Brand Y - Bromate (µg/L)					
Temperature pH	20	30	40	50	Storage Time
6.5	=	=	=	=	1 Day
	+	+	+	+	14 Days
	-	-	-	-	42 Days
7.5	+	+	+	+	1 Day
	+	+	+	+	14 Days
	+	+	+	+	42 Days
8.5	+	+	+	+	1 Day
	+	+	+	+	14 Days
	+	+	+	+	42 Days

Table A.30: Brand Z Bromate behavior (Reference: temperature 20°C and pH 6.5)

Brand Z - Bromate (µg/L)					
Temperature pH	20	30	40	50	Storage Time
6.5	=	=	=	=	1 Day
	-	-	-	-	14 Days
	Nil	Nil	Nil	Nil	42 Days
7.5	=	=	=	=	1 Day
	-	-	-	-	14 Days
	Nil	Nil	Nil	Nil	42 Days
8.5	+	+	+	+	1 Day
	-	-	-	-	14 Days
	Nil	Nil	Nil	Nil	42 Days

Vita

Haifa Ismail Mohammad Sharif was born on June 5th, 1990, in Dubai, UAE. She received her high school certificate from Dawha American International School in Sharjah, UAE in 2007. She was awarded the Bachelor of Science degree in Civil Engineering from the American University of Sharjah, UAE in August, 2011. She immediately began her Master of Science program in Civil Engineering at the same university in September, 2011. During her graduate studies, she worked for Dubai Electricity and Water Authority as an Asset Management Engineer in Transmission Maintenance Department, Transmission Power Division.