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Probabilistic Estimation of Bromate Exposure from the Consumption of Bottled Drinking Water Distributed in the Bogor Region

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ABSTRACT

Bottled drinking water is a source of human exposure to bromate, a disinfection by-product (DBP) with adverse health effects and carcinogenic potential. Little is known about bromate exposure levels and risk characterization, particularly in Bogor, Indonesia. The study aimed to obtain data on bromate concentrations in bottled drinking water, estimate bromate exposure levels based on individual consumption, and assess the risk characterization. Bromate exposure were calculated based on bromate concentrations and individual consumption, across five age groups. Bromate exposure and risk characterization were estimated probabilistically using Monte Carlo simulation. In this study, 37 bottled drinking water samples were collected from large and small manufacturers and retailers in Bogor and analyzed for bromate content. Bromate was detected in 30 samples, with 5 samples exceeding the Indonesian national standard of 10 µg/L. The average concentration was 6.88±8.88 µg/L. Exposure estimates indicate that, for all age groups, the average and 95th percentile values are 0.1086±0.0484 µg/kg BW/day and 0.4044 µg/kg BW/day in Bogor and 0.1492±0.2820 µg/kg BW/day and 0.5495 µg/kg BW/day in Indonesia, respectively. Values below the tolerable daily intake (TDI) limit for non-cancer risk, so the risk characterization for all age groups can be considered as safe.

1. INTRODUCTION

Water is an essential nutrient due to its role in hydrating the body and comprising approximately 60% of an adult's body weight (Jéquier & Constant, 2010). Adequate hydration supports the effective function of the lungs, respiratory tract, digestive system, and reproductive system. Water also aids in the excretion of waste and toxins from the kidneys, thus preventing kidney stones (Sontrop *et al*., 2013). In the skin, water plays a role in maintaining skin elasticity and resilience (Williams *et al*., 2007). Dehydration causes the nervous system to function suboptimally, leading to impaired cognitive function (Cian *et al*., 2001).

The recommended daily water intake varies by age group (Kemenkes, 2019). For children, the recommended daily water intake is 1650-1850 mL, and for adults, 2350-2500 mL/person/day. Drinking water contributes 70-80% of total water intake, approximately 1,320-1,480 mL/day (children) and 1,880-2,000 mL/day (adults) (Jéquier & Constant, 2010). With changing lifestyles and the need for convenience, the commercialization of drinking water products has been widely implemented in the form of bottled drinking water (AMDK). As of July 2024, there were 9,245 bottled drinking water products registered with the National Agency Drug and Food Control of Indonesia (NADFC). The consumption trend for bottled drinking water has also increased annually, reaching 49.03% of households in West Java and 40.64% of households in Indonesia in 2023.

During the bottled drinking water production process, disinfection is carried out to eliminate the dangers of pathogenic microbes carried in the raw water. *Cryptosporodium parvum oocysts* and *Giardia cysts*, waterborne pathogens, cannot be controlled by chemical disinfectants due to their resistance to chlorine (Wolf *et al*., 2018). However, it can be controlled by a disinfection process using ozone at a specific dose. Inactivation of 1 log at 10ºC requires a dose of 0.5 mg/(L.min) for *Giardia* and 2.5-10 mg/(L.min) for *Cryptosporidium* (Amy *et al*., 2000). Ozonation is a widely used disinfection method due to its highly reactive ability to inactivate microorganisms (Wibawa & Sururi 2023).

Ozonation is an effective method for disinfecting bottled drinking water, but the process can cause the conversion of bromide to bromate (Winid, 2019; Morrison *et al*., 2023). This bromate compound can cause problems for human health. Based on its carcinogenicity, IARC (2019) classifies bromate as group 2B (possibly carcinogenic to humans). Furthermore, non-cancer toxicity data for acute exposure indicate negative effects on the gastrointestinal tract followed by kidneys.

Based on data that bromate can pose a risk to health problems due to consuming bottled drinking water products, it is necessary to estimate bromate exposure through the stages of exposure calculation and risk characterization. This study aims to: 1) Obtain data on bromate concentrations in bottled drinking water circulating in the Bogor area; 2) Estimate the level of bromate exposure based on individual consumption data; 3) Obtain an overview of the level of health risk from bromate due to consuming bottled drinking water. The results of this study are expected to be one of the exposure study models with a probabilistic approach and the results can be used as consideration for the government in formulating policies related to the dangers of bromate content in bottled drinking water circulating.

2. MATERIALS AND METHODS

2.1. Materials

The study used primary and secondary data. Primary data consisted of bromate test results in bottled water samples. Secondary data consisted of body weight, age, and bottled water consumption data was based on the SKMI report on Individual Food Consumption Survey from the Ministry of Health (2014).

2.2. Methods

2.2.1. Bromate Testing in Bottled Water Samples

A total of 37 bottled water products were randomly sampled from large and small retailers in the Bogor area. The samples came from different manufacturers to obtain a variety of results. Bromate content testing used ion chromatography at a KAN-accredited laboratory in accordance with SNI 3554:2015 (BSN, 2015). This method is a quantitative analysis technique that separates various component mixtures based on their ion affinity for ion-exchange resins.

2.2.2. Bottled Water Consumption Data Collection

The secondary data used were age, body weight, and individual consumption of bottled water (code: 162002) from the 2014 SKMI report in $mL·person^{-1}·day^{-1}$. Consumption data were processed for bottled water consumers in the Bogor and Indonesian populations, then divided into five age groups: 6-59 months, 5-12 years, 13-18 years, 19-55 years, and over 55 years. Consumption data from Bogor respondents were used to calculate bromate exposure in the Bogor population. Consumption data from all respondents in Indonesia were used to estimate bromate exposure in the Indonesian population.

2.2.3. Bromate Exposure Calculation

Daily bromate exposure, or estimated daily intake (EDI), is measured by multiplying the amount of bottled water consumed ($mL·person^{-1}·day^{-1}$) by the bromate concentration in the bottled water sample (µg/L), divided by the respondent's body weight (kg). This yields an exposure value expressed in µg/kg body weight/day according to Equation (1).

$$\text{Exposure value (EDI)} = \frac{\textit{Amount consumed} \times \textit{Bromate concentration}}{\textit{Body weight} \times 1000} \quad (1)$$

Bromate exposure values were calculated for the Bogor population by developing bromate exposure calculations for the Indonesian population using bromate concentration data from samples taken at large retailers. This assumes that samples sold at large retailers are also sold in other trading areas in Indonesia. Bromate exposure was then used to calculate risk characteristics for each age group.

2.2.4. Bromate Risk Characterization

Risk characterization (HQ) was measured by comparing the bromate exposure value or EDI (µg·[kg BW]$^{-1}$·day^{-1}) with the tolerable daily intake (TDI) reference value of 1 µg·[kg BW]$^{-1}$·day^{-1} (WHO, 2005), according to Equation (2).

$$\textit{Risk characterization } (HQ) = \frac{\textit{Exposure value } (EDI)}{\textit{TDI value}} \quad (2)$$

The TDI value is the safe limit for daily exposure over a lifetime. This value was calculated from the No Observed Adverse Effect Level (NOAEL), the highest dose of bromate that shows no adverse effects in test animals, which is 1.3 µg·[kg BW]$^{-1}$·day^{-1} (Kurokawa *et al*., 1986) with an uncertainty factor of 1000. A HQ value greater than 1 indicates a risk from bromate exposure; conversely, a value less than 1 indicates no risk from bromate exposure.

2.2.5. Data Modeling and Analysis

Bromate concentration data were analyzed to obtain minimum, maximum, mean, median, 5th percentile, 25th percentile, 75th percentile, and 95th percentile values. Individual consumption and bromate concentration data were processed using Excel. Probabilistic distributions of bromate concentration, individual consumption amount, and body weight, as well as Monte Carlo simulations for exposure and risk characterization, were processed using @Risk (Lumivero, US). Distribution fitting to each parameter, concentration, consumption amount, and body weight, was used to determine a distribution model that represented the distribution of the input data. A 10-15% cutoff at the minimum and maximum values of the distribution model was necessary to limit the distribution and account for uncertainty. Simulations were performed in 50,000 iterations to achieve stable results and data convergence.

3. RESULTS AND DISCUSSION

3.1. Bromate Concentration in Bottled Drinking Water

Of 37 bottled drinking water samples from different manufacturers and sampled in the Bogor area, bromate was detected in 30 (81%). Bromate concentrations ranged from undetectable (< 0.4 µg/L to 40 µg/L [Table 1]). Concentrations indicating undetectability are expressed as half the limit of detection, which is 0.2 µg/L (limit of detection : 0.4 µg/L), to consider the worst-case risk in exposure calculations (WHO, 1995). The average bromate concentration across all samples was 6.88±8.88 µg/L. This value is still below the maximum bromate limit of 10 µg/L (BSN, 2023).

Table 1. Bromate concentration in bottled drinking water samples across different categories

Category	Number of Samples	% Positive Bromate Samples	Samples Exceeding Maximum Limit (> 10 µg/L)	Bromate Concentration (µg/L)		
				Minimum	Maximum	Mean±SD
Retail scale						
Large	20	95%	3	0.2	40	9.28±10.07
Small	17	65%	2	0.2	20	4.05±6.42
Industrial scale						
Medium/Large	26	81%	4	0.2	40	8.09±9.72
Micro/Small	11	82%	1	0.2	20	4.00±5.88
Factory origin						
Bogor	23	83%	4	0.2	40	7.73±10.48
Non Bogor	14	79%	1	0.2	20	5.47±5.39
Total	**37**	**81%**	**5**	**0.2**	**40**	**6.88±8.88**

However, there were 5 (13.5%) outliers, namely samples with concentrations of 20 µg/L, 30 µg/L, and 40 µg/L, which exceeded the maximum limit.

Bottled drinking water samples circulating in Bogor were then identified based on retail scale, industrial scale, and factory of origin (Table 1). The results showed that bottled drinking water sold in large retailers had a higher average bromate concentration (9.28±10.07 µg/L) than samples sold in small retailers (4.05±6.42 µg/L). Samples sold in large retailers typically originate from medium/large-scale industries. This is also evident in the higher average bromate concentration for samples produced by medium/large-scale industries (8.09±9.72 µg/L) compared to samples from micro/small-scale industries (4.00±5.88 µg/L).

A Nigerian study measuring bromate content in bottled drinking water in the Aba Metropolis area reported average bromate concentrations in bottled and sachet water of 4.09±0.44 µg/L and 5.07±0.78 µg/L, respectively (Irogbeyi *et al*., 2019). Another Kuwaiti study also reported an average bromate content of 4.02 µg/L in bottled drinking water (Al-Qallaf & Alali, 2022). Alomirah *et al*. (2019) reported a bromate concentration of 2.89 µg/L in bottled drinking water samples. The average bromate content in bottled drinking water samples in Bogor was slightly higher than those in both Nigerian and Kuwaiti studies, but still below the maximum permissible limit for bromate contaminants.

Differences in bromate concentration are influenced by several factors, including: the naturally occurring bromide content in raw water, the conditions and design of the ozonation process, namely the ozone dose and contact time used, and the chemical and physical characteristics of the water, such as pH (Yang *et al*., 2019). Aljundi (2011) shows that increasing the initial bromide concentration can increase bromate production, provided there is adequate ozone availability. The relationship between bromate formation and ozone concentration and exposure time follows a linear function, where increasing ozone concentration time (*Ct*) increases bromate formation (Jarvis *et al*., 2007). Conversely, in situations where ozone is insufficient, bromate yield decreases as bromide levels increase. All other factors being equal, bromide concentration and ozone dose are the best predictors of bromate formation (WHO, 2005).

In ozonation, bromate formation generally increases at high pH. High pH conditions accelerate the reaction of ozone with OH^- to produce OH^- radicals, which oxidize bromide to bromate. Conversely, a low pH will shift the $HOBr/OBr^-$ equilibrium to HOBr, which is more resistant to oxidation to bromate. Therefore, lowering the pH is typically used to control bromate formation during ozonation (Yang *et al*., 2019). Based on the bromate concentration data in the studied samples and the AMDK production process, the high bromate content is likely influenced by the ozone dosage used in large/medium and micro/small industries, as well as other specific conditions.

3.2. Bottled Drinking Water (AMDK) Consumption Data

3.2.1. Bogor Respondents

The respondents who consumed bottled drinking water in the Bogor population consisted of 162 individuals, represented by 90 men and 72 women, predominantly in the 19–55 age range. Data on the distribution body weight of respondents within each age group is shown in Table 2. Body weight of respondents in Bogor ranged from 7.8 kg to 119.7 kg, with an average of 52.9±18.2 kg. The relatively large standard deviation indicates significant variation in body weight. This supports probabilistic approaches that simulate individual uncertainty within a population. Body weight (BW) is an important factor in determining exposure values because it acts as a denominator that negatively

Table 2. Body weight (kg) and bottled water consumption levels of Bogor population

Age Group	Body Weight (kg)				Daily Consumption of Bottled Water (mL/person)			
	Min	Max	Mean±SD	P-95*	Min	Max	Mean±SD	P-95*
6–59 months (*n* = 8)	7.8	14.8	11.9±2.8	14.6	45	960	410±363	946
5–12 years (*n* = 19)	19.5	47.8	31.3±8.4	45.6	120	1192	447±304	1109
13–18 years (*n* = 21)	31.8	119.7	51.5±19.6	84.6	220	1560	532±364	1240
19–55 years (*n* = 107)	38.0	100.3	59.5±12.2	80.9	120	3600	883±774	2488
> 55 years (*n* = 7)	45.7	79.8	61.4±13.2	79.8	166	2475	1182±1017	2452
All ages (*n* = 162)	7.8	119.7	52.9±18.2	79.8	45	3600	776±712	2317

Source: Processed data from SKMI, Kemenkes (2014)

* The value indicating that 95% of the population has values equal to or lower than P-95

correlates with exposure. The greater weight of an individual, the lower the exposure value. Furthermore, the amount of food consumed also influences exposure.

The consumption level of bottled water among Bogor respondents per person/day ranged from 45 mL to 3600 mL with an average of 776±712 mL (Table 2). The average value of bottled water consumption in each age group increased with age, in sequence: 410±363 mL, 447±304 mL, 532±364 mL, 883±774 mL, and 1182±1017 mL. The high standard deviation in the level of drinking water consumption indicates that bottled water consumption in the Bogor community has a very high variation. When compared to the recommended daily drinking water intake, the majority of people in Bogor have not met the recommended amount of drinking water consumption. The amount of drinking water consumption per person per day is met at the 95th percentile value or 5% of the population with the highest consumption. The P-95 value, as shown in Table 2, means that 95% of the population in Bogor has a consumption level equal to or below the P-95 value, and only 5% of the population has a value above it.

The average body weight for those aged 6–59 months was 11.9±2.8 kg, for those aged 5-12 years 31.3±8.4 kg, for those aged 13-18 years 51.5±19.6 kg, for those aged 19-55 years 59.5±12.2 kg, and for those aged 55 years and older 61.4±13.2 kg. These average body weight data align with the nationally determined body weight data in the regulation of Minister of Health regarding recommended nutritional adequacy for the Indonesian population (Table 3).

Table 3. Reference body weight and drinking water consumption levels

Age Group	Body Weight (kg)	Recommended Dietary Allowance of Total Water (mL/person/day)	Drinking Water Requirement (mL/person/day)
6–59 months	9-19	900-1450	720-1160
5–12 years	19-38	1650-1850	1320-1480
13–18 years	48-60	2100-2300	1680-1840
19–55 years	55-60	2350-2500	1880-2000
> 55 years	53-60	1400-2500	1120-2000

Source: Processed data from the ministry of health regulation on recommended dietary allowances for the Indonesian population, Kemenkes (2019)

In calculating bromate exposure from bottled water consumption, this drinking water consumption data is important because it will positively correlate with the exposure value. The higher the consumption level of bottled water containing bromate, the higher the exposure value.

3.2.2. Indonesian Respondents

A total of 15,806 Indonesian respondents, consisting of 7,832 women and 7,974 men, consumed bottled water. The majority of respondents were in the adult age group, 19–55 years old (9,127 individuals). In general, across all age groups, the body weight of bottled water consumers ranged from 5.5 kg to 129.8 kg, with an average of 52.8±17.8 kg (Table 4). The distribution of weight data by age group is as follows: toddlers (6–59 months) gained 13.3±3.3 kg, children (5–12 years) gained 29.2±10.4 kg, adolescents (13–18 years) gained 48.0±11.1 kg, adults (19–55 years) gained 61.2±12.3 kg, and seniors (> 55 years) gained 58.8±12.5 kg (Table 4).

At ages 6–59 months, weight changes were relatively small. More significant weight gains occurred at ages 5–12, followed by ages 19–55. This indicates a more intense phase of growth and physiological changes at these ages. Weight gain continued at ages 19–55, but the rate slowed with increasing age within this range. At the age of > 55 years, insignificant growth can be seen from the average weight value which decreased from the 19–55 year age group.

Table 4. Body weight (kg) of bottled water consumers in the Indonesian population [Processed data from SKMI, Kemenkes (2014)]

Age Group	Body Weight (kg)				Bottled Water Consumption (mL/person/day)			
	Min	Max	Mean±SD	P-95	Min	Max	Mean ± SD	P-95
6–59 months (*n* = 537)	5.5	20.9	13.3±3.3	19.6	10	2000	369±287	956
5–12 years (*n* = 2273)	7.5	89	29.2±10.4	49	48	3900	515±417	1350
13–18 years (*n* = 2366)	14.3	119.7	48.0±11.1	68.6	80	4800	587±525	1634
19–55 years (*n* = 9127)	18.1	129.8	61.2±12.3	83.1	18	7820	860±702	2190
>55 years (*n* = 1503)	22.2	108.7	58.8±12.5	80	60	4243	879±653	2182
All ages (*n* = 15806)	5.5	129.8	52.8±17.8	80	10	7820	754±648	2000

Daily consumption for bottled water among respondents across all age groups ranged from 10 to 7,820 mL/person, with average of 754±648 mL/person. The high variability in drinking water consumption levels among Indonesian populations, such as those in Bogor, provides a basis for extrapolating bromate exposure calculations in Bogor to the Indonesian population.

Across all age groups, the 95th percentile indicates that Indonesians consume a maximum of 2,000 mL of bottled water per person per day. Under normal physical activity, this value is within the recommended daily water intake (Table 3). However, some individuals may consume as much as 7,820 mL/day, even under extreme conditions such as high physical activity and certain physiological conditions. Differences in daily activity, physiological conditions, and lifestyle also influence individual bottled water consumption patterns. The daily drinking water requirement for the Indonesian population is also not met for the majority of people across all age groups, reaching only the 95^{th} percentile. The daily consumption of bottled water per person at the 95th percentile across all age groups, as shown in Table 4, aligns with the recommended maximum daily intake for each age group as shown in Table 3.

3.3. Bromate Exposure Level

Bromate exposure levels due to bottled water consumption were calculated as Estimated Daily Intake (EDI) using a probabilistic approach using 50,000 iterations in a Monte Carlo simulations. This method considers variations in the distribution of the parameters used, thus providing more accurate exposure estimates. This approach uses not only average values but also distributions that reflect individual variability. Each parameter, bromate concentration, consumption level, and body weight was assigned a probabilistic distribution using distribution fitting in Monte Carlo software, as in Table 5.

Table 5. Monte Carlo simulation parameters in bromate exposure assessment

Parameter	Unit	Distribution Model	Cut Off
Bromate Concentration (μg/L)	μg/L		
a. Large and small retail samples (*n* = 37)		Exponential	(0.2;44)
b. Large retail samples (*n* = 20)		Exponential	(0.2;44)
Consumption Data (Bogor respondents)			
a. Body Weight	kg		
6–59 months old (*n* = 8)		Normal	(7.5;15)
5–12 years old (*n* = 19)		Normal	(19.5;48)
13–18 years old (*n* = 21)		Log Normal	(31;119)
19–55 years old (*n* = 107)		Log Normal	(38;100)
> 55 years old (*n* = 7)		Normal	(45.5;80)
All ages (*n* = 162)		Normal	(7;120)
b. Daily Water Intake	(mL/person)		
6–59 months old (*n* = 8)		Exponential	(45;960)
5–12 years old (*n* = 19)		Log Normal	(120;1192)
13–18 years old (*n* = 21)		Log Normal	(220;2560)
19–55 years old (*n* = 107)		Log Normal	(120;3600)
> 55 years old (*n* = 7)		Log Normal	(160;2500)
All ages (*n* = 162)		Log Normal	(45;3600)
Consumption Data (Indonesian respondents)			
a. Body Weight	kg		
6–59 months old (*n* = 537)		Normal	(5.5;20.9)
5–12 years old (*n* = 2273		Log Normal	(7.5;89)
13–18 years old (*n* = 2366)		Log Normal	(14;120)
19–55 years old (*n* = 9127)		Log Normal	(18;130)
> 55 years old (*n* = 1503)		Normal	(22;109)
All ages (*n* = 15806)		Normal	(5.5;130)
b. Daily Water Intake	(mL/person)		
6–59 months old (*n* = 537)		Log Normal	(10;2000)
5–12 years old (*n* = 2273)		Log Normal	(48;3900)
13–18 years old (*n* = 2366)		Log Normal	(80;4800)
19–55 years old (*n* = 9127)		Log Normal	(18;7820
> 55 years old (*n* = 1503)		Log Normal	(60;4243)
All ages (*n*=15806)		Log Normal	(10;7820)

3.3.1 Probabilistic Distribution of Bromate Concentrations

The bromate concentrations used in calculating bromate exposure for the Bogor population were derived from the probabilistic distribution of bromate concentrations from all 37 samples of bottled water (both large and small retailers). Meanwhile, the calculation of bromate exposure for the Indonesian population used 20 bottled water samples from large retailers. The assumption is that the bottled water samples sold at these large retailers are also sold in other regional trading areas and consumed by the Indonesian population. The probabilistic distributions for bromate concentrations from both the total sample and the samples from large retailers follow an exponential distribution model. This was based on the good fit of the input data distribution graph and the lower AIC (Akaike Information Criterion) values for the exponential model [220.84 (total) and 134.95 (large retailers)] compared to the other distribution models. AIC is a measure for selecting the best model by balancing model fit and complexity. A lower AIC value indicates the most efficient model and fits the data best (Burnham & Anderson, 2002).

The truncation of the exponential distribution curve is intended to provide boundaries and account for uncertainty. The minimum value is capped at 0.2 µg/L, which is half the limit of detection, which is 0.4 µg/L, to accommodate the possibility of very low bromate concentrations declared undetectable in the analysis results. The maximum value is capped at 44 µg/L, a 10% increase from the maximum analysis value (40 µg/L) to accommodate the possibility of bromate concentrations higher than the input data.

The probabilistic distribution of bromate concentrations can be seen in Table 6. In general, bromate concentrations in samples from large retailers tend to be higher than those in the overall sample. Although the cutoff and distribution model used in both samples are the same, namely exponential, the data distributions show different variations. The average bromate concentration in the large retail samples was 8.925±8.172 µg/L, higher than the average for all samples, which was 6.814±6.469 µg/L. Similarly, the percentile values at P5, P25, P50, P75, and P95 indicate that the distribution of bromate concentrations from large retailers was consistently higher than the bromate concentrations in all samples. This may contribute to the possibility that bromate exposure results in the Indonesian population using bromate concentration data from large retailers are greater than bromate exposure for the Bogor population.

Table 6. Results of probabilistic distribution of bromate concentration in the bottled drinking water

Value	Bromate concentration from all samples* (µg/L)		Bromate concentration from large retail samples† (µg/L)	
	Input Data	Probabilistic Distribution	Input Data	Probabilistic Distribution
Minimum	0.2	0.2	0.2	0.201
Maximum	40	43.664	40	43.983
Mean	6.876	6.814	9.28	8.925
SD	8.878	6.469	10.07	8.172
Percentile-5	0.2	0.541	0.2	0.662
Percentile-25	0.8	2.117	2	2.787
Percentile-50	5	4.817	7	6.42
Percentile-75	8	9.424	10	12.568
Percentile-95	30	20.01	30	26.11

Data on bromate concentration used in bromate exposure assessment for the population: *) Bogor, and †) Indonesia

3.3.2. Probabilistic Distribution of Body Weight and Consumption Amount

The calculation of bromate exposure through bottled water consumption was based on individual daily consumption data for each age group. The probabilistic method models the distribution of body weight parameters and individual daily consumption amounts. This distribution allows for exposure estimates that take into account individual variation within the population, allowing for more precise calculation of bromate exposure per unit body weight. Furthermore, the age-specific distribution of body weight facilitates more detailed and relevant risk characterization for specific subpopulations (Portier *et al*., 2007).

The selection of the distribution model was based on the results of fitting the distribution of each dataset per age group, both for respondents in the Bogor region and respondents in Indonesia (Table 5). The distribution of body weight data generally followed a normal and log-normal distribution model. In general, for all age groups, ages 6–59 months and ages 55 years and older in Bogor and Indonesian respondents, the distribution of body weight followed a normal distribution model. The normal distribution model for body weight was also used to calculate bromate exposure in a study in India (Kumar *et al*., 2011). Meanwhile, for ages 13–18 and 19–55, the weight distribution model follows a lognormal model, meaning the logarithm of weight follows a normal distribution. This aligns with Portier *et al*. (2007), that the weight distribution of respondents in the United States closely matches a log-normal distribution. The probabilistic distribution results for weight in the Bogor and Indonesian populations are shown in Tables 7 and 8.

Table 7. Probabilistic results for body weight in the population in Bogor

Age Group	Body Weight (kg)							
	Minimum	Maximum	Mea±SD	P-5	P-25	P-50	P-75	P-95
6–59 months	7.5	15.0	11.5±1.9	8.3	10.1	11.6	13.1	14.5
5–12 years	19.5	48.0	32.2±6.7	21.6	27.0	31.9	37.0	43.8
13–18 years	31.0	119.0	50.5±14.7	34.4	39.9	46.6	56.8	80.7
19–55 years	38.0	100.0	59.4±11.6	43.2	50.9	57.9	66.4	81.3
> 55 years	45.5	80.0	62.1±8.9	48.0	55.1	62.0	69.0	76.9
All ages	7.0	119.9	53.2±17.8	23.9	40.9	53.0	65.3	82.9

Table 8. Probabilistic results of body weight in the population in Indonesia

Age Group	Body Weight (kg)							
	Minimum	Maximum	Mean±SD	P-5	P-25	P-50	P-75	P-95
6–59 months	5.5	20.9	13.3±3.1	8.1	11.1	13.3	15.5	18.5
5–12 years	8.7	88.8	29.2±10.3	16.1	21.8	27.3	34.4	48.8
13–18 years	15.8	112.9	48.0±10.9	32.0	40.3	47.0	54.6	67.5
19–55 years	25.5	128.9	61.2±12.3	43.2	52.5	60.1	68.6	83.1
> 55 years	22.0	108.3	58.9±12.4	38.5	50.4	58.8	67.2	79.4
All ages	5.5	124.8	53±17.5	24.1	40.9	52.9	64.8	82.1

The distribution model for daily bottled water consumption among Indonesian respondents follows a log-normal model for all ages and by age group. The graph forms an asymmetric curve with a long tail on the right side. The log-normal distribution model was also applied to the distribution of bottled water consumption data among Bogor respondents for all ages and by age group, except for those aged 6-59 months. In this age group, the log-normal distribution does not follow a log-normal pattern; instead, the consumption distribution is conservatively determined to follow an exponential distribution model. The probabilistic distribution results for the Bogor and Indonesian populations are shown in Tables 9 and 10.

Table 9. Probabilistic results for the daily water consumption in Bogor population

Age Group	Daily Water Intake (mL/person)							
	Minimum	Maximum	Mean±SD	P-5	P-25	P-50	P-75	P-95
6–59 months	45	960	329±229	62	140	269	471	797
5–12 years	120	1,192	406±226	154	236	344	518	889
13–18 years	220	2,560	491±403	226	253	326	536	1,408
19–55 years	120	3,600	799±646	189	346	583	1,026	2,214
> 55 years	166	2,475	1,271±610	311	773	1,255	1,755	2,286
All ages	45	3,600	725±599	141	309	540	939	1,992

Table 10. Probabilistic results for the daily water consumption in Indonesia population

Age Group	Water Intake (mL/person/day)							
	Minimum	Maximum	Mean±SD	P-5	P-25	P-50	P-75	P-95
6–59 months	10	1,998	364±279	75	172	289	471	921
5–12 years	49	3,892	507±396	140	251	392	628	1,266
13–18 years	85	4,792	573±502	155	263	416	694	1,530
19–55 years	35	7,808	863±760	182	379	638	1079	2,303
> 55 years	60	4,243	858±670	196	394	656	1098	2,252
All ages	26	7,787	753±682	153	325	552	940	2,030

3.3.3. Bromate Exposure Calculation Results

The results of Monte Carlo simulations estimating bromate exposure levels from bottled water consumption in the Bogor population and extending this to the Indonesian population are shown in Tables 11 and 12. The mean and 95th percentile values for bromate exposure, both overall and per age group, for Bogor and Indonesian respondents showed values below the TDI, which is 1 µg/kg BW/day. Bromate exposure in Indonesian respondents was higher than in Bogor respondents. This is due to the higher bromate concentration used to calculate exposure in Indonesian respondents.

Table 11. Probabilistic results for bromate exposure from bottled water consumption per age group in Bogor

Age Group	**Bromate Exposure (µg/kg BW/day)**							
	Min	**Max**	**Mean±SD**	**P-5**	**P-25**	**P-50**	**P-75**	**P-95**
6–59 months	0.0008	4.0812	0.1990±0.1011	0.0087	0.0383	0.1011	0.2456	0.7286
5–12 years	0.0007	1.8604	0.0902±0.0520	0.0052	0.0213	0.0520	0.1143	0.3025
13–18 years	0.0005	2.3365	0.0707±0.0370	0.0037	0.0155	0.0370	0.0819	0.2446
19–55 years	0.0003	2.7912	0.0949±0.0467	0.0044	0.0182	0.0467	0.1109	0.3461
> 55 years	0.0005	2.0369	0.1420±0.0837	0.0078	0.0332	0.0837	0.1870	0.4761
All ages	0.0002	4.8216	0.1085±0.0484	0.0040	0.0180	0.0484	0.1205	0.4044

Table 12. Probabilistic results for bromate exposure from bottled water consumption per age group in Indonesia

Age Group	**Bromate Exposure (µg/kg BW/day)**							
	Min	**Max**	**Mean±SD**	**P-5**	**P-25**	**P-50**	**P-75**	**P-95**
6–59 months	0.0003	7.8669	0.2601±0.3798	0.0104	0.0491	0.1315	0.3132	0.9264
5–12 years	0.0005	6.6180	0.1725±0.2567	0.0075	0.0341	0.0876	0.2053	0.6158
13–18 years	0.0004	4.2742	0.1121±0.1729	0.0048	0.0224	0.0563	0.1309	0.3982
19–55 years	0.0003	4.0424	0.1304±0.1999	0.0054	0.0245	0.0644	0.1538	0.4728
> 55 years	0.0003	4.4694	0.1365±0.2007	0.0059	0.0264	0.0691	0.1622	0.4964
All ages	0.0002	10.0241	0.1492±0.2820	0.0052	0.0247	0.0669	0.1642	0.5495

In the Bogor population, the average bromate exposure for toddlers (6–59 months) was higher than for other age groups, at 0.1990±0.1011 µg/kg BW/day. Meanwhile, the average exposure for adolescents (13–18 years) was lowest at 0.0707±0.0037 µg/kg BW/day. National bromate exposure in Indonesia was estimated using probabilistic distributions from consumption data among the Indonesian population and bromate concentration data from a sample of large retail bottled drinking water (AMDK) representing bottled water circulating in Indonesia. In the Indonesian population, the highest average exposure also occurred at the age of 6–59 months, namely: 0.2601±0.3798 µg/kg BW/day and the lowest was at the age of 13–18 years, namely: 0.1121±0.1729 µg/kg BW/day. A study in Kuwait showed the same thing that the bromate exposure value from bottled water consumption at the age of 3–5 years had the highest average exposure value compared to other age groups, namely: 0.13 µg/kg BW/day (Alomirah *et al.*, 2019). Similarly, research in Chile also reported that infants (0–1 years) and children (1–10 years) had the highest bromate exposure, at 0.447 µg/kg BW/day and 0.373 µg/kg BW/day, respectively (Calderon *et al.*, 2019).

Therefore, the 6–59 month age group is at higher risk compared to other age groups, particularly at the 95th percentile, where bottled water consumption is 797 mL (Bogor) and 921 mL (Indonesia). In toddlers, although bottled water consumption is lower than in other age groups, there is a smaller weight factor, resulting in higher exposure values. Bromate exposure for adults with a consumption level according to the recommended drinking water intake from the Ministry of Health (2,000 mL/person/day) can be estimated from the 95th percentile exposure values, which are 0.3461 (Bogor) and 0.4728 (Indonesia). At this consumption level, bromate exposure only reaches nearly half the safe daily exposure limit of 1 µg/kg BW (body weight).

A study in Nigeria measured the average bromate exposure due to bottled water consumption for adults with an average consumption of 2L/day, a body weight of 60.7 kg, and a life expectancy of 54.5 years at 0.129 µg/kg BW/day (bottled water) and 0.16 µg/kg BW/day (sachet water) (Irogbeyi *et al.*, 2019). When compared to adults in Bogor and Indonesia, the average exposure values were not significantly different, at 0.0949±0.0467 µg/kg BW/day and 0.1304±0.1999 µg/kg BW/day, compared to bromate exposure values in the Nigerian population.

3.4. Risk Characterization

The risk levels due to bromate exposure were estimated for five age groups (toddlers, children, adolescents, adults, and elderlies) using HQ values comparing bromate exposure and TDI (1 µg/kg BW/day). Calculations were performed using 50,000 Monte Carlo simulations. Overall, across all age groups in the Bogor, the average and 95% of the population showed a risk level < 1 (Table 13). This indicates no risk or acceptable risk level for Bogor respondents.

Table 13. Probabilistic results for bromate risk levels (HQ) per age group in Bogor

Age Group	HQ							
	Min	Max	Mean±SD	P-5	P-25	P-50	P-75	P-95
6–59 months	0.0008	4.0812	0.1990±0.1011	0.0087	0.0383	0.1011	0.2456	0.7286
5–12 years	0.0007	1.8604	0.0902±0.0520	0.0052	0.0213	0.0520	0.1143	0.3025
13–18 years	0.0005	2.3365	0.0707±0.0370	0.0037	0.0155	0.0370	0.0819	0.2446
19–55 years	0.0003	2.7912	0.0949±0.0467	0.0044	0.0182	0.0467	0.1109	0.3461
> 55 years	0.0005	2.0369	0.1420±0.0837	0.0078	0.0332	0.0837	0.1870	0.4761
All ages	0.0002	4.8216	0.1085±0.0484	0.0040	0.0180	0.0484	0.1205	0.4044

Table 14. Probabilistic results for bromate risk levels (HQ) per age group in Indonesia

Age Group	HQ							
	Min	Max	Mean±SD	P-5	P-25	P-50	P-75	P-95
6–59 months	0.0003	7.8669	0.2601±0.3798	0.0104	0.0491	0.1315	0.3132	0.9264
5–12 years	0.0005	6.6180	0.1725±0.2567	0.0075	0.0341	0.0876	0.2053	0.6158
13–18 years	0.0004	4.2742	0.1121±0.1729	0.0048	0.0224	0.0563	0.1309	0.3982
19–55 years	0.0003	4.0424	0.1304±0.1999	0.0054	0.0245	0.0644	0.1538	0.4728
> 55 years	0.0003	4.4694	0.1365±0.2007	0.0059	0.0264	0.0691	0.1622	0.4964
All ages	0.0002	10.0241	0.1492±0.2820	0.0052	0.0247	0.0669	0.1642	0.5495

Similarly, for Indonesian respondents, exposure values for all age groups were at the average level, and 95% of the population could be considered safe because they were below the tolerable intake limit for bromate (Table 14). Respondents aged 6–59 months had the highest average risk level, at 0.1990±0.1011 (Bogor) and 0.2601±0.3798 (Indonesia), compared to other groups. This age group requires attention because the 95th percentile value for Indonesian respondents was 0.9264, approaching the safe limit of 1. Risk levels with values greater than 1 across all age groups occurred in a small proportion of individuals with maximum exposure, namely respondents with a combination of high consumption and low body weight. This occurs in a portion of the population with extreme conditions. Therefore, this risk level is not considered representative of the majority of population exposure, and the analysis focused on the distribution of the majority, namely the 95th percentile value.

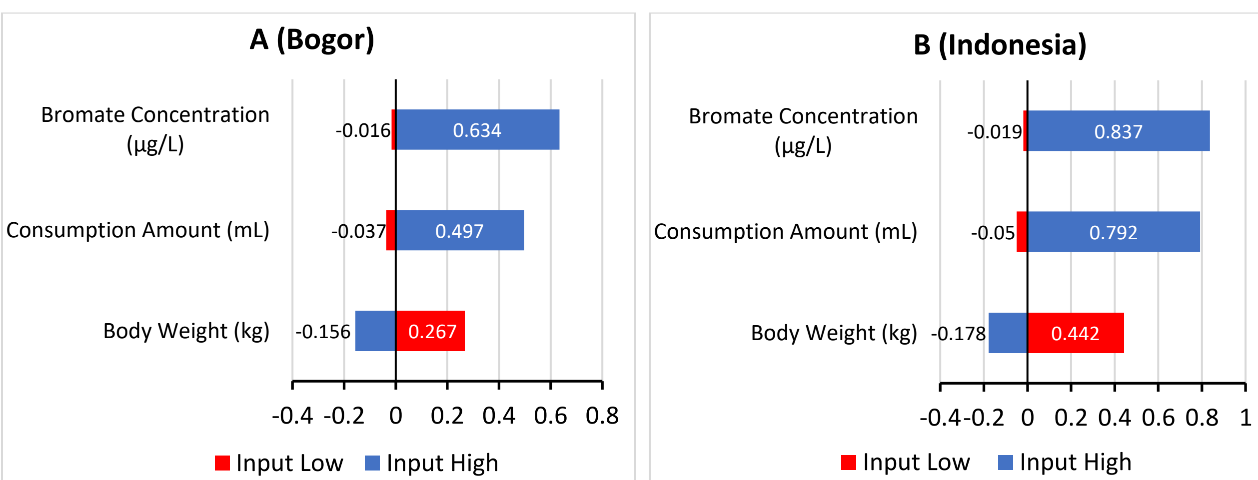

Figure 1. Sensitivity analysis graph of bromate risk values for respondents aged 6–59 months: A. Bogor, B. Indonesia

Based on the sensitivity analysis graph shown in Figure 1, bromate concentration has the greatest influence on the high risk level (HQ). When bromate concentrations are high, the HQ value increases significantly to 0.634 (Bogor) and 0.837 (Indonesia). Conversely, when bromate concentrations are low, there is a negative correlation, decreasing the HQ value by 0.016 (Bogor) and 0.019 (Indonesia). Therefore, quality control of bromide content, which is then converted to bromate due to ozonation in bottled drinking water, must be a constant concern for both bottled drinking water companies and the government. This is also very important, especially to implement the recommendation for daily consumption of drinking water 2000 mL/person, which has occurred in only 5% of the population.

4. CONCLUSION

In this study, 37 bottled water samples obtained from large and small retailers in the Bogor area contained bromate at concentrations ranging from < 0.4 µg/L to 40 µg/L, with an average of 6.88±8.88 µg/L, which meets the maximum bromate concentration limit for bottled water according to the Indonesian National Standard (SNI). Drinking water consumption levels in the Bogor and Indonesian populations are only at the 95th percentile, or 5% of the population. The estimated bromate exposure from bottled water consumption for both Bogor and Indonesian respondents indicates that the average and 95th percentile values are below the safe daily bromate exposure limit. Therefore, overall, the mean and 95th percentile values for bromate risk (HQ) is below 1, indicating low risk and can be considered safe, with HQ values of 0.1085±0.0484 and 0.4044 (Bogor) and 0.1492±0.2820 and 0.5495 (Indonesia). Further studies may focus on expanding the sampling scope, including both bottled water types, sample size, and sampling area, as well as the latest individual consumption data to improve the accuracy of the results.

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