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Health Risk Assessment of Chloroform in Swimming Pools: A Case Study in Lampang Province, Thailand

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Abstract

Chloroform (CF) is a toxic disinfection by-product commonly found in swimming pool water. Research on CF levels in swimming pool water and their associated health risks is limited in Thailand. This study aimed to assess the concentration of CF and the health risks associated with the CF exposure among swimmers in the Mueang Lampang district, Lampang province, Thailand. Pool water samples were collected using grab sampling during the summer of 2024. A total of 139 swimmers were surveyed to obtain demographic data and swimming habits, and the data were analyzed using Stata software. The results showed that the outdoor pool had the highest average CF concentration of 63.89 ± 12.76 µg/L. A health risk assessment revealed that all four groups of swimmers (children, teenagers, adult females, and adult males) faced the highest risk from inhalation exposure to CF, followed by dermal absorption and ingestion. In term of non-cancer health risks, all groups demonstrated acceptable risk levels based on U.S.EPA guidelines (Hazard Index: HI < 1) across all three types of swimming pools. For lifetime cancer risk, the outdoor pool posed unacceptable risk for both adult female and adult male groups ($> 10^{-4}$), while the indoor and semi-outdoor pools presented acceptable risk levels (10^{-6} - 10^{-4}). Therefore, it is recommended that swimmers consider reducing the frequency and duration of their sessions to mitigate health risks associated with CF exposure. Additionally, swimming pool operators should implement regular water quality monitoring programs, focusing on free chlorine residuals and optimizing chlorine dosing.

Keywords: Chloroform; Clean water; Risk assessment; Swimming pool

1. Introduction

Swimming is a popular form of exercise and recreation, especially during the summer. It is suitable for all genders and ages, promoting muscle strengthening throughout the body. The number of swimming pool facilities has been increasing, offering various options, including indoor, semi-outdoor, and outdoor pools. However, if pools are not properly maintained and water quality is not monitored according to established academic standards, they can become sources of disease outbreaks (MPH, 2007). A study of disease outbreaks in swimming pools in the United States between 2015 and 2019 identified 3,646 cases, including 286 hospitalizations and 13 deaths. There were 208 confirmed outbreaks, with 155 (75%) attributed to infectious agents, including parasites in 80 outbreaks (38%), bacteria in 72 outbreaks (35%), and viruses in 3 outbreaks (1%). The remaining 53 outbreaks had unconfirmed causes but were suspected to be related to chemical factors, such as excessive chlorine, disinfection by-products (DBPs), or chemical changes in the pool

(Hlavsa *et al.,* 2021). In Thailand, swimming pools are classified as regulated businesses deemed hazardous to health under Section 31 of the Public Health Act B.E. 2535 and its subsequent amendments (MPH, 2015).

Disinfection of swimming pools is essential for preventing waterborne diseases. Chlorine is the most commonly used disinfectant due to its affordability, availability, and high efficacy in killing pathogens. However, chlorine use leads to the formation of DBPs, which result from the reactions of free chlorine and organic matter in the source and filling water, as well as human excretions from swimmers. Organic matter in water is recognized as the main precursor for DBPs formation. The concentration of organic matter in water is commonly measured as total organic carbon (TOC). Previous studies have demonstrated a strong correlation between TOC levels and DBPs concentrations. This relationship is likely due to the fact that higher TOC levels indicate a greater organic load in the pool water, which can interact with disinfectants to form DBPs (Peng *et al.,* 2020; Genisoglu *et al.,* 2023). These DBPs include trihalomethanes (THMs), haloacetic acids (HAAs), and haloacetonitriles (HANs), with THMs being the most commonly detected (Zhang *et al.,* 2023). The THMs group consists of four main compounds: chloroform (CF), bromodichloromethane (BDCM), dibromochloromethane (DBCM), and bromoform (BF). CF and BDCM are classified as group B2 carcinogens, meaning they are possible human carcinogens, while DBCM and BF are classified as group 3 carcinogens, indicating they are not classifiable as to their carcinogenicity in humans (IARC, 1999). Previous research has shown that THMs concentrations in indoor and outdoor swimming pools in Northern Greece can vary significantly, with levels ranging from 1 to 410 μg/L (Sdougkou *et al.,* 2021). Many studies have indicated that CF has the highest concentration among the THMs species (Chatsantiprapa *et al.,* 2020; Peng *et al.,* 2020; Shi *et al.,* 2020; Wang and Dong, 2020; Sdougkou *et al.,* 2021; Zhang *et al.,* 2023; Zheng *et al.,* 2023). Some studies report that the CF concentration in swimming pools range from 0.025 to 0.484 μg/L in the summer and from 0.676 to 1.576 μg/L in the winter (Dehghani *et al.,* 2022). In Sweden, chloroform concentrations in indoor pools ranged from 0.08 to 20.1 μg/L (Ragnebro *et al.,* 2023). In China, the concentration of CF in indoor swimming pools was ranged from 4.9 to 101.9 μg/L (Shi *et al.,* 2020), and 25.60 to 40.55 μg/L (Zheng *et al.,* 2023). A study in Thailand on CF concentrations in three types of pools (indoor, semi-outdoor, and outdoor) revealed inconsistent findings. Some studies reported the highest CF levels in semi-outdoor pools (37.67 to 59.10 μg/L), followed by outdoor and indoor pools (Briwichayawisut, 2009; Rodwinij, 2009). Other research in Thailand indicated that outdoor pools had the higher CF concentrations, ranging from 34.86 to 150.35 μg/L (Do, 2012).

THMs can be absorbed by the human body through ingestion, dermal absorption, and inhalation. Once absorbed, these compounds can accumulate in tissues such as fat, liver, and kidneys, depending on the concentration and route of exposure (Amy *et al.,* 2000). They have been associated with various adverse health effects, including irritation to the eyes, skin, and respiratory system, as well as effects on the central nervous system. Additionally, evidence links exposure to THMs with an increased risk of bladder cancer (Beane Freeman *et al.,* 2017), colorectal cancer (Jones *et al.,* 2019; Shi *et al.,* 2024), and endocrine-related cancers (Shi *et al.,* 2024). Due to the dangers posed by THMs, the World Health Organization (WHO) and regulatory bodies worldwide, including those in Thailand, have set maximum allowable concentrations (MCLs) for CF, BDCM, DBCM, and BF in drinking water and tap water at 300, 60, 100, and 100 μg/L, respectively (WHO, 2017; MWA, 2022).

Due to the limited studies on DBPs in swimming pools in Thailand, the researcher became interested in investigating the concentration of THMs in swimming pools in the Mueang Lampang District, Lampang Province. The criteria for selecting indoor, semi-outdoor, and outdoor pools are based on the fact that each pool type exhibits distinct levels of DBPs and is associated with different health risks. The data obtained from the study are used to assess the health risks associated with THMs exposure among Thai swimmers. This study focuses on four swimmer groups: children, teenagers, adult females, and adult males. These groups were selected due to physiological differences (e.g., age, weight, and height) as well as variations in swimming behaviors, which may influence THM exposure risks. The key contribution of this research lies in its collection of data from actual swimmers through interviews and questionnaires, ensuring a representative sample of the Thai population across age groups. This approach provides a more reliable foundation for calculating health risk values associated with THMs exposure. Additionally, this study presents data on THMs levels in various pool types. Recommendations for pool maintenance are also provided to enhance swimmer safety and health.

2. Methodology

2.1 Water sample collection

Water samples were collected during summer (April to May, 2024) from three types of swimming pools (indoor, semi-outdoor, and outdoor pools) using the grab sampling method. The characteristics of each pool type are as follows: the outdoor pool is fully open to the environment, with no roof or enclosure; the indoor pool is entirely enclosed with a roof; and the semi-outdoor pool is partially enclosed, with one section roofed and the other open to the environment. These pools are located in difference areas of the Muang Lampang district, Lampang province, Thailand. All pools are public facilities used for recreational and athletic purposes, with chlorine employed as the primary disinfectant. Sampling points were designated at four locations along the corners of the pool, with samples taken 50 cm from the walls at a depth of 20 to 30 cm below the water surface, a level that allows for full body contact with the water (Briwichayawisut, 2009; Sdougkou *et al.,* 2021). The combined water samples were then split into three 250 mL bottles. The first bottle was used to analyze the free chlorine residual concentration immediately on-site at the sampling location. The second bottle was used to measure total organic carbon (TOC), a parameter used to assess the concentration of organic compounds in a water sample. This sample was acidified by adding 1.25 mL of 2M hydrochloric acid (RCI Labscan, Thailand) to eliminate inorganic carbon. The third bottle was used to analyze the THMs concentration. The sample was preserved by adding 2M acetic acid (Carlo Erba, France) to prevent THMs degradation and adding ascorbic acid (Kemaus, Australia) at twice the free chlorine concentration to quench chlorine reaction. All samples were then stored at 4 ± 2 °C before analysis in the laboratory.

2.2 Water sample preparation and analysis

Free chlorine residual concentration was analyzed using a chlorine portable colorimeter (DR900, HACH, USA). TOC was measured by a TOC/total nitrogen analyzer (TOC/TN, multi-N/C 3100, Analytik Jena, Germany). The concentration of THMs was analyzed using a gas chromatography-mass spectrometry (GC-MS, 8890 (GC) and 5977B (MS), Agilent, USA). Prior to GC-MS analysis, the water sample were extracted using a modified U.S. EPA 551.1 liquid-liquid extraction method (Kiattisaksiri *et al.,* 2020). The limits of detection (LOD) for all THMs species were 0.25 μg/L. The calibration curves utilized in the THMs analysis demonstrated strong correlation coefficients (R^2) of no less than 0.995. All tests were conducted in duplicate, and both the average and standard deviation were determined.

2.3 Study population

The study population consisted of swimmers from three swimming pools, selected using purposive sampling. The inclusion criteria for the study population were (1) being 7 years of age or older and (2) being able to communicate, read, listen, write, and answer questions in Thai. There were no exclusion and withdrawal/discontinuation criteria in this study. Data on average daily users from March to May 2023 were obtained from pool owners to determine the sample size of the study population. The sample included 139 swimmers: 62 from the indoor swimming pool, 27 from the outdoor swimming pool, and 50 from the semi-outdoor swimming pool. This research received ethics approval for human studies from the Human

Research Ethics Committee at Thammasat University (Science; COA No.035/2567) and the Human Research Ethics Committee at Boromarajonani College of Nursing, Nakhon Lampang (No. E2567-025).

2.4 Exposure assessment

The exposure assessment involves selecting populations based on age groups and exposure pathways. These selections are then used to evaluate the risk of chemical exposure as follows: (1) The population is divided into four groups: children aged 7 to 11 years (hereafter referred to as “children”), teenagers aged 12 to 17 years (hereafter referred to as “teenagers”), adult females, and adult males; (2) Exposure routes are categorized into three pathways: ingestion, dermal absorption, and inhalation. Following U.S.EPA standard methods, exposure was assessed using equation (1) to (4) (U.S.EPA, 2015; Zhang *et al.,* 2023), which incorporate parameters recommended by the U.S.EPA and data collected from questionnaires.

$$CDI_{ingestion} = (Cw \times IGR \times ED \times EF \times ET) / (BW \times AT) \quad (1)$$

$$CDI_{dermal} = (Cw \times F \times SA \times Kp \times ED \times EF \times ET) / (BW \times AT) \quad (2)$$

$$CDI_{inhalation} = (Cair \times IR \times ED \times EF \times ET) / (BW \times AT) \quad (3)$$

$$C_{air} = Cw \times HLC \times 1000 \quad (4)$$

Where $CDI_{ingestion}$, CDI_{dermal}, and $CDI_{inhalation}$ are chronic daily intake values for ingestion, dermal absorption, and inhalation (mg/kg/day), respectively; Cw is CF concentration in water (mg/L); IGR is ingestion rate (mL/hr); ED is exposure duration (years); EF is exposure frequency (day/year); ET is exposure time (hr/day); BW is body weight (kg); AT is average time (day); F is conversion factor for water volume (1 L/1000 cm^3); SA is skin surface area (cm^2); Kp is skin permeability coefficient (cm/hr); C_{air} is chemical concentration in the air (mg/m^3); HLC is Henry’s law constant; and IR is respiratory rate (m^3/hr). Values for calculation are provided in Table 1 and 2.

Table 1. Data used for risk assessment of CF exposure

Variables	Unit	Children	Teenager	Adult female	Adult male	Data sources
IGR	mL/hr	50	50	25	25	U.S. EPA, 2015
ED	years	4	4	30	30	U.S. EPA, 2003
EF	day/year	138.88	147.87	219.75	212.50	This study
ET	hr/day	1.42	1.50	3.65	2.93	This study
IR	m^3/hr	1.3	1.5	1.0	1.0	U.S. EPA, 2015
BW	kg	32.13	56.40	55.00	76.25	This study
SA	cm^2	10,837	15,858	15,730	19,161	This study
AT	day	1,460	1,460	10,950	10,950	ED × 365

Note: IGR is the ingestion rate; ED is the exposure duration for non-cancer risk; EF is the exposure frequency; ET is the exposure time; IR is the inhalation rate; BW is body weight; SA is the surface area of the skin, calculated using the Mosteller formula; and AT is the average time.

Table 2. The constants used for risk assessment of CF exposure

Variables	Unit	Constants for CF	Data sources
SF			
-Ingestion	1/(mg/kg/day)	6.10×10^{-3}	Nadali et al., 2019
-Dermal absorption	1/(mg/kg/day)	3.05×10^{-2}	Nadali et al., 2019
-Inhalation	1/(mg/kg/day)	8.10×10^{-2}	Nadali et al., 2019
RfD	mg/kg/day	1.00×10^{-2}	Zhang *et al*., 2023
Kp	cm/hr	0.0089	U.S.EPA, 2015
HLC	unitless	0.0037	Zhang *et al*., 2023

Note: SF is the slope factor; RfD is the reference dose; Kp is the skin permeability coefficient; and HLC is Henry’s law constant for CF at 24 °C.

2.5 Health risk assessment

The hazard index (HI; unitless) is used to assess non-cancer health risks. An HI of less than 1.0 indicates an acceptable level of risk, while an HI greater than 1.0 suggests an unacceptable risk. HI can be calculated using Equation (5) (U.S.EPA, 2009).

$$HI = CDI / RfD \qquad (5)$$

Where RfD is the reference dose (mg/kg/day).

The total hazard index (total HI; unitless) is calculated by summing the individual HIs for the ingestion, dermal absorption, and inhalation routes, as shown in Equation (6) (U.S.EPA, 2009).

$$\text{Total HI} = HI_{ingestion} + HI_{dermal} + HI_{inhalation} \qquad (6)$$

A lifetime cancer risk (unitless) within the range of 10^{-6} to 10^{-4} is generally considered acceptable according to the U.S.EPA. It can be calculated using Equation (7) (U.S.EPA, 2009).

$$\text{Lifetime cancer risk} = CDI \times SF \qquad (7)$$

Where SF is the slope factor (1/(mg/kg/day)), as presented in Table 2.

2.6 Data analysis

Data analysis of water quality, exposure and health risk calculation was conducted using a Microsoft Excel 2019 under Windows 11. Statistical analysis of the study population was performed with Stata version 14.0. Descriptive statistics, including the mean, standard deviation, minimum, and maximum values, were calculated to summarize the results.

3. Results and Discussion

3.1 Free chlorine residual

The study on free chlorine residual in three swimming pools found that the levels ranged from 0.01 to 15.03 mg/L. The outdoor pool exhibited the highest average concentration of free chlorine residual at 7.17 ± 6.49 mg/L, followed by indoor pool (0.33 ± 0.34 mg/L) and semi-outdoor pool (0.04 ± 0.06 mg/L), as shown in Table 3. When compared to the standard water quality guidelines for swimming pools, which specify a range of 0.6 to 1.0 mg/L (MPH, 2007), none of the pools met the standard. Two of the three swimming pools had residual free chlorine levels below the standard. The indoor and semi-outdoor pools exhibited lower levels of free chlorine residual, while the outdoor pool had higher levels. This discrepancy may be attributed to a higher chlorine dosage in the outdoor pool compared to the other pools. When comparing the residual free chlorine levels, it was found that the values were similar to those reported in previous studies conducted in Thailand, with residual free chlorine levels ranging from 0.09 to 9.80 mg/L (Briwichayawisut, 2009; Do, 2012). Variations in residual free chlorine levels among the pools can be attributed to factors such as chlorine dosage and raw water quality (Kraisin, 2016).

3.2 TOC concentration

The study on TOC found that levels ranged from 21.30 to 119.10 mg/L. The semi-outdoor pool had the highest average TOC at 116.93 ± 2.40 mg/L, followed by the outdoor pool (65.87 ± 3.92 mg/L) and the indoor pool (23.23 ± 1.83 mg/L), as detailed in Table 3. The variation in TOC among the swimming pools is attributed to organic matter from the raw water used to fill the pools, organic compounds from swimmer's bodies, and environmental factors surrounding the swimming pools (Rodwinij, 2009; Teo *et al.,* 2015; Genisoglu *et al.,* 2023). The water in the outdoor and semi-outdoor pools contained a greater variety of CF precursors, such as grass, leaves, insects, and rain, which may contribute to elevated precursor contamination levels. Additionally, higher residual free chlorine and TOC levels may account for the increased CF levels.

Table 3. Results of water quality analysis for swimming pools (n = 3)

Number of samplings	Water quality		
	Residual chlorine (mg/L ± SD)	TOC (mg/L ± SD)	CF (µg/L ± SD)
1) Indoor pool			
1	0.70 ± 0.00	25.15 ± 0.09	15.24 ± 0.20
2	0.52 ± 0.02	21.30 ± 0.03	7.69 ± 0.16
3	0.01 ± 0.01	24.38 ± 0.08	18.70 ± 1.75
4	0.08 ± 0.00	22.08 ± 0.02	11.24 ± 0.25
average	0.33 ± 0.34	23.23 ± 1.83	13.22 ± 4.79
2) Outdoor pool			
1	1.61 ± 0.02	64.01 ± 0.01	51.32 ± 3.81
2	15.03 ± 0.06	67.21 ± 0.13	80.46 ± 1.78
3	9.94 ± 0.05	70.65 ± 0.12	66.81 ± 1.54
4	2.09 ± 0.04	61.62 ± 0.00	56.99 ± 2.58
average	7.17 ± 6.49	65.87 ± 3.92	63.89 ±12.76
3) Semi-outdoor pool			
1	0.01 ± 0.00	113.50 ± 0.12	23.78 ± 0.82
2	0.02 ± 0.00	117.50 ± 0.24	15.95 ± 0.46
3	0.01 ± 0.00	117.60 ± 0.41	12.70 ± 0.75
4	0.13 ± 0.00	119.10 ± 0.15	13.63 ± 0.49
average	0.04 ± 0.06	116.93 ± 2.40	16.52 ± 5.03

3.3 Chloroform concentration

Among the four THMs, CF was the only one detected in significant concentrations in this study. The other THMs, including BDCM, DBCM, and BF, were found to below the LOD, and were therefore not reported in this study. The concentrations of CF in the swimming pools ranged from 7.69 to 80.46 µg/L. The outdoor pool had the highest mean CF concentration (63.89 ± 12.76 µg/L), followed by the semi-outdoor (16.52 ± 5.03 µg/L) and the indoor pool (13.22 ± 4.79 µg/L) as shown in Table 3.

Since there are no established standards for CF in swimming pool in Thailand, the drinking water and tap water quality standard were used as references. In this study, the concentration of CF in swimming pool was found to be below the MCLs of 300 µg/L (WHO, 2017; MWA, 2022). These findings are consistent with previous research indicating that CF concentrations in swimming pools in Nakhon Pathom Province (26.15 to 65.09 µg/L) and Yala Province (34.86 to 150.35 µg/L) were also below the drinking water and tap water quality standards (Panyakapo *et al.,* 2008; Do, 2012).

When considering the factors influencing the formation of CF in swimming pools, previous studies have shown that precursor substances, including levels of free chlorine residual and TOC, affect the concentration of CF (Janthong, 2010; Do, 2012). These findings align with this study, which showed that the outdoor pool had the highest levels of residual free chlorine, leading to higher CF concentrations compared to the other pools. Interestingly, while the indoor pool had higher levels of residual free chlorine than the semi-outdoor pool, it exhibited lower CF concentrations. This was attributed to the influence of TOC, which were five times higher in the semi-outdoor pool than in the indoor pool. Therefore, the concentration of CF in swimming pools should be evaluated by considering both precursor factors: residual free chlorine alongside TOC.

3.4 Study population results

The study population involved 139 swimmers, of whom 61.15% were male and 38.85% were female. The swimmers included 68 children (48.92%), 31 teenagers (22.30%), 16 adult females (11.51%), and 24 adult males (17.27%). The swimmers' weights ranged from 16 to 110 kg, and their heights ranged from 113 to 190 cm. The mean weight of children, teenagers, adult females, and adult males were 32.13 ± 11.44, 56.40 ± 15.67, 55.00 ± 9.11, and 76.25 ± 12.14 kg, respectively. The mean heights of children, teenagers, adult females, and adult males were 131.59 ± 10.99, 160.52 ± 8.17, 161.94 ± 4.85, and 173.33 ± 6.27 cm, respectively. The demographic profile of swimmers is shown in Table 4.

Regarding swimming duration and frequency, the study found that swimming time ranged from 0.5 to 10 hr/day, and swimming frequency ranged from 12 to 360 days/year. When categorized by group, adult females had the longest average swimming duration and frequency at 3.65 ± 2.41 hr/day and 219.75 ± 157.54 days/year, respectively, followed by adult males, teenagers, and children. Detailed data on swimmers are presented in Table 5.

3.5 Exposure and health risk assessment

3.5.1 Exposure assessment

Swimmer can be exposed to DBPs via ingestion, dermal absorption by the skin, and inhalation of volatile compound. Swimmers can be exposed to CF in pools through ingestion, primarily due to accidental swallowing (Shi *et al.,* 2020). In this study, the highest CF exposure via the ingestion pathway for children, teenagers, adult females, and adult males was 5.37×10^{-5}, 3.44×10^{-5}, 6.38×10^{-5}, and 3.57×10^{-5} mg/kg/day, respectively (Table 6-8). The highest CF exposure through skin absorption for children, teenagers, adult females, and adult males was 1.04×10^{-4}, 9.72×10^{-5}, 3.57×10^{-4}, and 2.44×10^{-4} mg/kg/day, respectively (Table 6-8). The highest CF exposure by inhalation for children, teenagers, adult females, and adult males was 5.17×10^{-3}, 3.82×10^{-3}, 9.45×10^{-3}, and 5.29×10^{-3} mg/kg/day, respectively. Adult females had the highest exposure values due to their longer swimming duration and frequency, as shown in Table 5. In terms of exposure pathways, all groups were most exposed through inhalation, with a maximum exposure of 9.45×10^{-3} mg/kg/day, followed by skin absorption and ingestion. This study aligns with previous research that identified inhalation and dermal absorption as the two primary exposure routes for CF due to its percutaneous absorption and volatile properties (Yang *et al.,* 2018; Dehghani *et al.,* 2022; Sdougkou *et al.,* 2021). Furthermore, in this study, the outdoor pool exhibited the highest exposure to CF, with CF concentrations approximately 4 – 5 times greater than those observed in the other pools. However, several factors impact exposure levels, such as pool temperature, chlorine dosage, number of swimmers, and ventilation systems, which should be studied in future research.

Table 4. Demographic profile of swimmers (n = 139)

Group of swimmers	Mean ± SD	
	Weight (kg)	Height (cm)
Children	32.13 ± 11.44	131.59 ± 10.99
Teenager	56.40 ± 15.67	160.52 ± 8.17
Adult female	55.00 ± 9.11	161.94 ± 4.85
Adult male	76.25 ± 12.14	173.33 ± 6.27

Table 5. Swimming pools usage data of swimmers (n = 139)

Characteristic	Min	Max	Mean ± SD
Swimming duration (hr/day)	0.5	10	1.5 ± 1.50
Children			1.42 ± 0.69
Teenager			1.50 ± 0.19
Adult female			3.65 ± 2.41
Adult male			2.93 ± 1.93
Swimming frequency (days/year)	12	360	162.91 ± 127.29
Children			138.88 ± 102.96
Teenager			147.87 ± 129.37
Adult female			219.75 ± 157.54
Adult male			212.50 ± 146.61

3.5.2 Non-carcinogenic health risk

The HI value represents the non-carcinogenic health risk from CF exposure (Table 6 - 8). The highest total HI values from the three exposure pathways of children, teenagers, adult females, and adult males were 5.33×10^{-1}, 3.95×10^{-1}, 9.87×10^{-1}, and 5.57×10^{-1}, respectively. The HI value for all sample groups were within the acceptable range defined by the U.S. EPA (HI $\leq$ 1.0), indicating that non-carcinogenic risk is not a significant concern. This finding aligns with previous studies, which indicate that all groups using the three types of swimming pools (indoor, semi-outdoor, and outdoor) have acceptable risk levels for non-cancer health effects (Do, 2012; Chatsantiprapa *et al.,* 2020; Wang and Dong, 2020; Sdougkou *et al.,* 2021). When comparing the different types of pools, the highest HI value was observed in the outdoor pool. This finding is consistent with previous research, which indicates that non-cancer risk values in outdoor pools are significantly higher than those in indoor pools (Ounsaneha *et al.,* 2017).

3.5.3 Carcinogenic health risk

The maximum total lifetime cancer risk of children, teenagers, adult females, and adult males was 2.41×10^{-5}, 1.79×10^{-5}, 3.33×10^{-4}, and 1.87×10^{-4}, respectively (Table 6-8). According to U.S.EPA guidelines, a risk value higher than 10^{-4} indicates a potential cancer risk (U.S.EPA, 2009). The results of this study indicated that the maximum total lifetime cancer risk for all groups of swimmers using indoor and semi-outdoor pools was acceptable (10^{-6} - 10^{-4}). For the outdoor pool, the cancer risk for children and teenagers was also deemed acceptable. However, unacceptable cancer risk (> 10^{-4}) was observed in adult females and males using the outdoor pool, attributed to their longer duration and frequency of swimming. Furthermore, the unacceptable cancer risk was found only in the outdoor pool due to the highest concentrations of CF compared to the other pools. Inhalation posed the greatest cancer risk for adult females using the outdoor pool, with a value of 3.33×10^{-4}. This finding aligns with previous studies in Thailand and other countries' swimming pools, which reported that inhalation was the primary route of exposure for all swimmers (Briwichayawisut, 2009; Sdougkou *et al.,* 2021). This is likely due to the high volatility of CF, which allows it to easily evaporate and contaminate the air.

3.5.4 Recommendations for minimizing health risks

The primary factors impacting the formation of CF in pool water are the levels of free chlorine residual and the presence of organic matter. Pool owners or attendants should maintain the free chlorine residual in swimming pools within the recommended

Table 6. Health risk assessment of CF in indoor swimming pool

Risk assessment	Group of swimmers: Children	Teenager	Adult female	Adult male
1.Exposure assessment (mg/kg/day)				
Ingestion	1.11×10^{-5}	7.12×10^{-6}	1.32×10^{-5}	7.39×10^{-6}
Absorption	2.14×10^{-5}	2.01×10^{-5}	7.39×10^{-5}	5.04×10^{-5}
Inhalation	1.07×10^{-3}	7.90×10^{-4}	1.95×10^{-3}	1.09×10^{-3}
Total	1.10×10^{-3}	8.18×10^{-4}	2.04×10^{-3}	1.15×10^{-3}
2.Non-cancer risk assessment (or HI)				
Ingestion	1.11×10^{-3}	7.12×10^{-4}	1.32×10^{-3}	7.39×10^{-4}
Absorption	2.14×10^{-3}	2.01×10^{-3}	7.39×10^{-3}	5.04×10^{-3}
Inhalation	1.07×10^{-1}	7.90×10^{-2}	1.95×10^{-1}	1.09×10^{-1}
Total	1.10×10^{-1}	8.18×10^{-2}	2.04×10^{-1}	1.15×10^{-1}
3.Cancer risk assessment				
Ingestion	3.87×10^{-9}	2.48×10^{-9}	3.45×10^{-8}	1.93×10^{-8}
Absorption	3.74×10^{-8}	3.50×10^{-8}	9.66×10^{-7}	6.59×10^{-7}
Inhalation	4.95×10^{-6}	3.66×10^{-6}	6.78×10^{-5}	3.80×10^{-5}
Total	4.99×10^{-6}	3.70×10^{-6}	6.88×10^{-5}	3.87×10^{-5}

range of 0.6 - 1.0 mg/L, as specified by the Ministry of Public Health, Thailand. A reduction in TOC is associated with decreased DBPs formation. Strategies to reduce TOC levels include improving pool water recirculation by integrating granular activated carbon (GAC) with sand filtration (Chau *et al.,* 2025). Organic matter can originate from swimmers' bodies, including substances such as sweat, saliva, urine, and residues from personal care products. To effectively reduce the introduction of organic matter, swimmers should shower for at least 60 seconds before entering the pool (Keuten *et al.,* 2012). Additionally, to minimize health risks associated with CF exposure, swimmers may consider reducing the frequency and duration of their pool sessions.

4. Conclusion

The concentration of free chlorine residual and TOC in three types of chlorinated swimming pools (indoor, semi-outdoor, and outdoor) in Mueang Lampang district, Lampang Province, Thailand, ranged from 0.01 to 15.03 mg/L, and 21.30 to 119.10 mg/L, respectively. The outdoor pool exhibited the highest average free chlorine residual at 7.17 ± 6.49 mg/L, followed by the indoor and semi-outdoor pools. The semi-outdoor pool had the highest average TOC level at 116.93 ± 2.40 mg/L, followed by the outdoor and indoor pools. CF concentrations in the swimming pools ranged from 7.69 to 80.46 µg/L, with the outdoor pool exhibited the highest average

Table 7. Health risk assessment of CF in outdoor swimming pool

Risk assessment	Group of swimmers			
	Children	Teenager	Adult female	Adult male
1.Exposure assessment (mg/kg/day)				
Ingestion	5.37×10^{-5}	3.44×10^{-5}	6.38×10^{-5}	3.57×10^{-5}
Absorption	1.04×10^{-4}	9.72×10^{-5}	3.57×10^{-4}	2.44×10^{-4}
Inhalation	5.17×10^{-3}	3.82×10^{-3}	9.45×10^{-3}	5.29×10^{-3}
Total	5.33×10^{-3}	3.95×10^{-3}	9.87×10^{-3}	5.57×10^{-3}
2.Non-cancer risk assessment (or HI)				
Ingestion	5.37×10^{-3}	3.44×10^{-3}	6.38×10^{-3}	3.57×10^{-3}
Absorption	1.04×10^{-2}	9.72×10^{-3}	3.57×10^{-2}	2.44×10^{-2}
Inhalation	5.17×10^{-1}	3.82×10^{-1}	9.45×10^{-1}	5.29×10^{-1}
Total	5.33×10^{-1}	3.95×10^{-1}	9.87×10^{-1}	5.57×10^{-1}
3.Cancer risk assessment				
Ingestion	1.87×10^{-8}	1.20×10^{-8}	1.67×10^{-7}	9.34×10^{-8}
Absorption	1.81×10^{-7}	1.69×10^{-7}	4.67×10^{-6}	3.19×10^{-6}
Inhalation	2.39×10^{-5}	1.77×10^{-5}	3.28×10^{-4}	1.84×10^{-4}
Total	2.41×10^{-5}	1.79×10^{-5}	3.33×10^{-4}	1.87×10^{-4}

Table 8. Health risk assessment of CF in semi-indoor swimming pool

Risk assessment	Group of swimmers			
	Children	Teenager	Adult female	Adult male
1.Exposure assessment (mg/kg/day)				
Ingestion	1.39×10^{-5}	8.90×10^{-6}	1.65×10^{-5}	9.24×10^{-6}
Absorption	2.68×10^{-5}	2.51×10^{-5}	9.24×10^{-5}	6.30×10^{-5}
Inhalation	1.34×10^{-3}	9.88×10^{-4}	2.44×10^{-3}	1.37×10^{-3}
Total	1.38×10^{-3}	1.02×10^{-3}	2.55×10^{-3}	1.44×10^{-3}
2.Non-cancer risk assessment (or HI)				
Ingestion	1.39×10^{-3}	8.90×10^{-4}	1.65×10^{-3}	9.24×10^{-4}
Absorption	2.68×10^{-3}	2.51×10^{-3}	9.24×10^{-3}	6.30×10^{-3}
Inhalation	1.34×10^{-1}	9.88×10^{-2}	2.44×10^{-1}	1.37×10^{-1}
Total	1.38×10^{-1}	1.02×10^{-1}	2.55×10^{-1}	1.44×10^{-1}
3.Cancer risk assessment				
Ingestion	4.84×10^{-9}	3.10×10^{-9}	4.31×10^{-8}	2.41×10^{-8}
Absorption	4.67×10^{-8}	4.38×10^{-8}	1.21×10^{-6}	8.24×10^{-7}
Inhalation	6.18×10^{-6}	4.57×10^{-6}	8.48×10^{-5}	4.75×10^{-5}
Total	6.23×10^{-6}	4.62×10^{-6}	8.60×10^{-5}	4.83×10^{-5}

CF at 63.89 ± 12.76 μg/L. This study reveals that free chlorine residual and TOC are key factors contributing to the formation of CF in swimming pools. Therefore, it is crucial for pool operators to regularly monitor and control these two factors to reduce the concentration of THMs in the swimming pools.

A health risk assessment conducted with four study groups consisting of 139 individuals revealed that inhalation was the dominant exposure pathway for CF. In the non-carcinogenic risk assessment, the adult female group exhibited the highest total HI value, followed by adult males, children, and teenagers, respectively. However, all groups showed acceptable levels of non-carcinogenic health risks (HI < 1). The lifetime cancer risk assessment revealed that both adult female and adult male groups had a potential cancer risk (> 10^{-4}) when using the outdoor pool with high CF levels for extended periods. The outdoor pool showed the highest cancer risk levels in adult females, with a value of 3.33×10^{-4}. It is recommended to provide risk reduction guidelines for pool owners or attendants. For instance, continuous monitoring and regular testing of water quality, including free chlorine residual, should be implemented. Additionally, it is important to ensure that chlorine is added in appropriate amounts. For swimmers, it is suggested to reduce the frequency and duration of swimming.

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