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Trihalomethanes in Latin American drinking water: Analysis of regulations, reported levels and advances in quantification methods

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Abstract

Trihalomethanes (THMs) in drinking water are a growing concern in Latin America due to their health risks and regulatory inconsistencies. This study examines existing regulations, detected levels, and analytical methodologies used across the region through a combined approach that includes bibliometric analysis, a systematic review of scientific literature, and a regulatory analysis. A comprehensive search of Web of Science and Scopus, using the search equation: "trihalomethanes" AND "water" AND "drinking," identified 73 relevant articles published between 2000 and 2024. The regulatory frameworks of all Latin American countries were analyzed. The study categorized countries based on their regulatory frameworks, compiled reported THM concentrations, and assessed advancements in analytical methodologies. The results reveal a pronounced regional disparity: while countries like Brazil, Colombia, Mexico, and Chile have developed regulatory frameworks and extensive research, other nations lack both regulations and studies entirely. The detected levels of THMs show significant variability, and in some cases, they far exceed the limits recommended by the World Health Organization (WHO), notably Brazil, with concentrations as high as 4220 µg/L. Analytical methodologies have evolved toward more efficient and environmentally sustainable techniques, such as headspace solid-phase microextraction (HS-SPME) and hollow fiber solvent bar microextraction (HF-SBME), enabling more precise detection in the ng/L to µg/L range. Effective strategies for controlling THMs were identified, including optimizing disinfection processes, removing precursors through nanofiltration and activated carbon, and using alternative disinfectants. The study highlights the urgent need for harmonized regulations, systematic monitoring, and increased research efforts to address knowledge gaps in THM contamination in drinking water across Latin America. The findings underscore the importance of implementing national and regional monitoring programs, developing evidence-based regulatory frameworks, and promoting research in underrepresented countries to ensure safe drinking water and mitigate public health risks.

Keywords: Disinfection by-products, Drinking water, Latin America, Public health, Trihalomethanes.

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1. Introduction

Various methods are used for disinfecting water, some of which use chemical disinfectants such as chlorine[1], ozone [2], iodine[3], hydrogen peroxide, and peracetic acid [4]. Physical methods include ultraviolet radiation [5] and ultrasonic waves [6]. Emerging technologies, such as advanced oxidation processes [7] and nanotechnology [8], have also been employed to provide less toxic and cost-effective alternatives for water disinfection.

Chlorination is the most widely used method for disinfecting drinking water. However, it has the disadvantage of forming by-products such as trihalomethanes (THMs), which pose a considerable health risk as they are classified as potentially carcinogenic to humans.

Health concerns associated with THMs in chlorinated drinking water have prompted some countries to investigate the levels of these by-products. However, many nations, particularly in Latin America, have yet to assess the presence of THMs in their water supplies. Despite well-documented risks, significant research and regulatory gaps regarding THMs in Latin America persist. The scarcity of systematic data on THMs concentrations and limited comparative analysis of regional regulatory standards hinder the development of effective mitigation strategies. Moreover, the inconsistent implementation of advanced analytical techniques, like microextraction methods, further complicates THMs detection and reporting. These combined challenges ultimately jeopardize access to safe drinking water in the region.

This study aims to assess THMs contamination in drinking water in Latin America by analyzing existing regulations, reported concentration levels, and advances in analytical quantification methods. Additionally, it seeks to identify regional disparities, highlight knowledge gaps, and provide recommendations for improving regulatory frameworks and monitoring strategies.

To address these gaps, this study seeks to answer the following key research questions: What regulatory frameworks exist in Latin America regarding THMs in drinking water? What are the reported THMs levels in different countries, and how do they compare with international guidelines? What analytical methodologies are used for THMs detection, and how have they evolved? What measures can be implemented to improve THMs regulation and monitoring in Latin America?

The remainder of this paper is organized as follows: Section 2 presents a comprehensive literature review on key aspects of THMs, including the benefits and drawbacks of chlorination, the mechanisms of THM formation, their associated health risks, and the current state of research in Latin America. Section 3 describes the methodology used for the bibliometric analysis and data collection. Section 4 presents a comparative analysis of THM regulations and detected levels in Latin America. This section also includes relevant information for problem mitigation, such as actions that can be taken to reduce or eliminate THMs in water, advances achieved in Latin America in analytical quantification methods, and alternative or combined methods with chlorination used to minimize the presence of THMs. Finally, Section 5 presents the conclusions of this research.

2. Literature Review

2.1. Benefits and Drawbacks of Chlorination

Chlorination remains the most widely used method for disinfecting drinking water globally due to its cost-effectiveness, ease of operation, and efficiency in eliminating a broad spectrum of pathogenic microorganisms, thus ensuring its potability [9]. A key advantage of chlorination is its ability to maintain a disinfectant residual within the distribution system, providing ongoing protection against potential recontamination [10]. Furthermore, chlorination processes are relatively easy to monitor and adjust to varying water quality parameters, making them a reliable option for many water treatment plants [11]. However, despite its widespread adoption and effectiveness, chlorination presents significant challenges, particularly concerning the formation of disinfection by-products (DBPs). While this is a global issue, it poses a particular concern for Latin America, where water quality treatment infrastructure and regulatory frameworks can vary considerably between and within countries [13]. These variations can significantly influence the types and concentrations of THMs formed, highlighting the need for region-specific research. Despite its drawbacks, chlorination's dominance can be attributed to the limited implementation and higher operational costs of alternative disinfection methods, such as ozonation or UV radiation, especially in developing regions. Consequently, understanding the complexities of chlorination and its by-product formation within the Latin American context is crucial for balancing the need for microbiological safety with minimizing chemical risks associated with DBPs.

2.2. Disinfection by-Product Formation During Chlorination

The main by-products formed during chlorination are trihalomethanes (THMs). The primary THMs formed during water chlorination are chloroform (CHCl3), bromodichloromethane (CHBrCl2), dibromochloromethane (CHBr2Cl), and bromoform (CHBr3). The formation of THMs during water chlorination involves chemical reactions between free residual chlorine and natural organic matter (NOM) present in the source waters of surface water bodies [14]. This process is influenced by factors such as chlorine reactivity, treatment conditions, and specific properties of water. The chlorine dose, reaction time, and the presence of bromide ions significantly impact the reactions leading to THMs formation [15, 16]. Additional variables, including pH levels, the type of organic matter in the water [17], and environmental parameters like hydrophilic NOM, water hardness, and apparent color, further promote THMs formation [18]. Crucially, the composition and reactivity of NOM can vary significantly depending on geographical location, climate, and land use patterns [19]. For example, water sources in tropical regions, prevalent in much of Latin America, may have higher concentrations of NOM derived from decaying vegetation, potentially leading to a higher THM formation potential. Despite this, there is a scarcity of research characterizing the specific types of NOM present in Latin American water sources and evaluating their reactivity with chlorine under conditions representative of the region's water treatment plants. This knowledge gap hinders the development of accurate predictive models for THM formation in Latin America and optimizing water treatment processes to minimize their production. Future research should, therefore, focus on bridging this gap to enable the design of tailored and effective strategies for mitigating THM formation in the diverse water sources across Latin America. Investigating the interplay between local NOM characteristics, varying operational practices in water treatment plants, and the influence of seasonal variations on these factors would be particularly valuable.

2.3. Health Risks of THMs

While chlorination is essential for disinfecting water, the formation of trihalomethanes (THMs) poses significant health risks. Trihalomethanes are classified as potentially carcinogenic to humans. Prolonged exposure to trihalomethanes, primarily through drinking water, has been associated with an increased risk of cancer, especially bladder cancer [20-23]. However, the extent to which these findings can be directly extrapolated to Latin American populations remains uncertain, given potential variations in exposure levels, water consumption patterns, and genetic susceptibility. In addition to cancer risks, epidemiological studies have suggested a possible association between exposure to THMs and adverse pregnancy outcomes, such as low birth weight, preterm birth, and congenital anomalies [24]. Non-carcinogenic risks associated with THMs also include potential impacts on liver, kidney, and central nervous system functions. Despite these concerns, the non-carcinogenic risk levels are generally within acceptable limits, indicating a relatively lower risk than their carcinogenic potential [25].

It is important to note that THM exposure can occur through multiple pathways, including ingestion, inhalation, and dermal absorption. While ingesting contaminated drinking water is often considered the primary route, inhalation, and dermal absorption during activities like showering, bathing, and swimming in chlorinated pools can also contribute to the overall body burden [26]. Dermal absorption, although a minor pathway, also contributes to the cumulative risk of THMs exposure. Studies suggest that the absorption of these compounds through the skin occurs during activities such as bathing and swimming in chlorinated water. However, the risks are significantly lower compared to ingestion and inhalation [27]. Nevertheless, the contribution of these different exposure routes might vary across Latin America depending on cultural practices, water usage habits, and the presence of indoor swimming pools. Limited data exists regarding the relative contribution of these pathways to overall THM exposure in Latin American populations.

2.4. Current State of THM Research in Latin America

Despite the well-established health risks associated with THMs and the widespread reliance on chlorination for water disinfection, research on THM contamination in Latin American drinking water is strikingly limited. A review of studies indexed in Web of Science and Scopus (up to February 2024) using the keywords "trihalomethanes," "water," and "drinking" reveals a disproportionately low contribution from Latin American researchers. Of the 3675 publications identified in Web of Science, only 103 (2.80%) originated from Latin American institutions. Similarly, in Scopus, only 41 of 2371 (1.72%) scientific articles were authored by researchers based in the region. This underrepresentation is particularly concerning given that Latin America accounts for approximately 8% of the world's population.

A lack of monitoring data further compounds the scarcity of published research. Recent global assessments on THMs indicate that at least 11 Latin American countries have no publicly available data on THM measurements in drinking water for human consumption [13]. This absence of fundamental monitoring data presents a major obstacle to understanding the magnitude and characteristics of THM contamination across the region. It suggests potential underreporting or severely limited monitoring capacity.

Critically, there is a notable lack of research investigating the region-specific factors contributing to THM formation in Latin America. As discussed in Section 2.2, the characteristics of NOM, specific water quality parameters, and operational practices at water treatment plants significantly influence THM formation. However, studies that systematically analyze these factors within Latin America's diverse hydrological and socio-economic contexts are scarce. This knowledge gap hinders the development of locally relevant and effective mitigation strategies. Several factors may contribute to this research deficit, including limited funding for environmental health research, insufficient analytical infrastructure, and competing public health priorities.

THM research in Latin America is characterized by a severe lack of data, methodological limitations in existing studies, and a crucial gap in understanding the region-specific drivers of THM formation and exposure. This contrasts with North America and Europe's more extensive research base. This study directly addresses these deficiencies by providing a comprehensive analysis of THM regulations across all Latin American countries, a comparative overview of reported THM levels, and an evaluation of the analytical methodologies used in the region. This integrated approach will provide a more accurate and nuanced understanding of THM contamination in Latin American drinking water, identify critical research needs, and inform evidence-based policies to improve water quality management and protect public health.

3.Materials and Methods

This study employed a mixed-methods approach, combining a bibliometric analysis with a systematic review of the scientific literature to achieve a comprehensive understanding of the research landscape concerning THMs in Latin American drinking water. This approach allows for both a quantitative assessment of research output (through bibliometric analysis) and a qualitative analysis of study findings, regulatory frameworks, and methodological advancements (through systematic review). The integration of these methodologies provides a more holistic view of the research gaps and challenges specific to Latin America than would be possible using a single approach. This combined approach differs from previous studies, which have often focused solely on literature reviews of THM levels [28] or on specific analytical techniques [29]. By integrating these methodologies, a more holistic view of the research gaps and challenges specific to Latin America is provided, encompassing not only scientific findings but also regulatory frameworks and methodological advancements.

3.1. Bibliographic Search and Selection Criteria

A bibliometric analysis was conducted to assess the scientific production of THMs in drinking water in Latin American countries. The literature search was carried out in February 2024 in two widely recognized databases: Web of Science (WoS) (Clarivate), which indexes approximately 21,973 journals, and Scopus (Elsevier), which covers around 47,680 journals. These databases were chosen for their comprehensive coverage of peer-reviewed scientific literature and their ability to provide detailed citation data.

The search equation used was: "trihalomethanes" AND "water" AND "drinking". The search was conducted in English. However, the search was limited to articles published in English and Spanish, as these are the predominant languages of scientific publication in Latin America. Filters were applied to include only original research articles published between 2000 and February 22, 2024. This timeframe was chosen to capture a sufficiently broad range of studies while focusing on relatively recent research. The search encompassed topics, titles, abstracts, and articles keywords. Importantly, the search was further refined by utilizing the built-in geographical filters available in Web of Science and Scopus. These filters allowed us to limit the search results directly to studies conducted in or explicitly about Latin American countries.

3.2. Article Selection

The initial search yielded 41 articles from Scopus and 103 from the Web of Science, resulting in 144 records. After removing 24 duplicates using Mendeley bibliographic management software, 120 articles remained. These articles underwent a two-stage selection process.

The following inclusion criteria were defined to ensure the relevant articles were selected:

- The articles had to be related to determining THMs in drinking water.
- They had to be focused on Latin American countries.

Studies that did not report specific THM levels or focus on other types of disinfectants or byproducts were excluded.

The first stage involved screening titles and abstracts based on the inclusion and exclusion criteria for relevance to the research topic. Articles that did not meet the criteria were excluded.

In the second stage, the full texts of the remaining articles were reviewed to confirm their eligibility. This process resulted in a final selection of 73 articles for detailed analysis.

3.3. Analysis of Legal Regulations

A comprehensive search was conducted across all Latin American countries to analyze the legal regulations concerning THMs in drinking water. The current regulations in each country were obtained from the official websites of relevant government institutions (e.g., Ministries of Health and Environmental Agencies) and, when necessary, from articles citing these regulations. The researchers prioritized official government sources to ensure the accuracy and authenticity of the regulatory information. The collected data were used to establish a comparative framework, contrasting the Maximum Permissible Values (MPVs) for total THMs and individual THMs (chloroform, bromodichloromethane, dibromochloromethane, and bromoform) across the region.

3.4. Data Analysis Methodology

The data extracted from the 73 selected articles were analyzed in four stages to address the research questions:

- Regulations: A comparative analysis of the current regulations on THMs in Latin American countries was conducted. Countries were classified based on whether they had regulations for THMs, and the MPVs for total and individual THMs were compared.
- THMs levels: The reported concentrations of THMs in drinking water from various Latin American studies were compiled. In cases where the studies reported several levels of THMs, the maximum measured values were taken for analysis and comparison. These reported levels were then compared with the MPVs established by the national regulations of each country and with international guidelines, such as those of the World Health Organization (WHO).

- Quantification methodologies: The analytical techniques employed for THM measurement in the reviewed studies were evaluated. This included an analysis of their evolution over time within Latin America. Additionally, a literature review focusing on the optimization of analytical methods for THMs was conducted, highlighting improvements in sensitivity, linearity, and analysis time.
- Alternative and combined methods: Articles exploring alternative or combined disinfection methods to minimize THMs formation were reviewed. This included studies on the combination of chlorination with other disinfection techniques and research on water pretreatment strategies aimed at reducing the levels of NOM, the precursors of THMs.

Python programming language was employed to generate graphical representations to facilitate the interpretation and visualization of the data.

4. Results and Discussion

4.1. Legal Regulations on THMs in Drinking Water in Latin America

The relationship between THMs and health problems has led the World Health Organization (WHO) and other international organizations to set maximum limits for their presence in drinking water. Most countries in Latin America have drinking water quality regulations that set maximum limits for various contaminants, including bacteria, heavy metals, and chemicals. Despite the importance of controlling the presence of THMs in drinking water, not all Latin American countries have established specific maximum limits for these by-products. According to available information, at least 11 countries in the region have incorporated limits for THMs into their national regulations. Table 1 summarizes the limits established for THMs in different Latin American countries' regulations, along with the recommendations from WHO and the European Union.

Table 1.
Regulatory limits of trihalomethanes in drinking water in Latin America and international references.

Country	Established limit (μg/L)				
	$CHCl_3$	$CHBrCl_2$	$CHBr_2Cl$	$CHBr_3$	TTHM
Brazil [30]	-	-	-	-	100
Colombia [31]	-	-	-	-	200
Chile [32]	200	60	100	100	Ratio = 1*
Costa Rica [33]	200	60	100	100	-
Ecuador [34]	300	60	-	-	500
El Salvador [35]	-	-	-	-	100 Ratio ≤ 1*
Honduras [36]	300	60	100	100	100
Mexico [37]	300	60	100	100	-
Panama [38]	-	-	-	-	100
Paraguay [39]	100	-	-	-	-
Dominican Republic [40]	200	60	100	100	-
WHO (Recommendation) [41]	300	60	100	100	Ratio ≤ 1*
European union (EU) [42]	-	-	-	-	100

Note: $CHCl_3$: Chloroform. $CHBrCl_2$: Dichlorobromomethane. $CHBr_2Cl$: Dibromochloromethane. $CHBr_3$: Bromoform. TTHM: Total trihalomethanes. *For TTHM, the sum of the ratios between the measured concentration of each compound and its respective upper limit must be less than or equal 1.

The heterogeneity in regulatory limits reflects the lack of a standardized approach to addressing the MST problem in the region. For example, as Brazil and the EU set a limit of 100 μg/L for TTHMs, Ecuador allows up to 500 μg/L, a significantly higher level than international recommendations. For example, the absence of national regulations in countries like Peru means that their population is exposed to unknown risks. All the above suggest establishing harmonized limits based on the recommendations of the WHO and other international agencies. This would strengthen regional collaboration by promoting the creation of a common regulatory framework that considers each country's particularities. The adoption of these measures would allow for better protection of public health in the region.

4.2. Detected Levels of THMs in Drinking Water from Studies Conducted in Latin America

Studies conducted in various Latin American countries have revealed significant variations in drinking water trihalomethane (THM) levels. Table 2 summarizes the most relevant findings from representative studies in the region, highlighting the concentrations of the main compounds detected (chloroform, bromodichloromethane, dibromochloromethane, and bromoform) and the TTHM values reported at various locations. Notably, the maximum recorded values were included in the table in studies with multiple measurements. Values in bold exceed the established limits.

Table 2.
Maximum levels of THMs detected in drinking water in Latin American countries.

Country	Location	Maximum levels detected (µg/L)					Ref.
		$CHCl_3$	$CHBrCl_2$	$CHBr_2Cl$	$CHBr_3$	TTHM	
Argentina	Bell Ville (Cordoba)	102.6					[43]
	San Marcos (Cordoba)	100.3					
	San Juan (San Juan) **	2.09	1.59	0.97	0.35		[44]
Brazil	Laguna do Peri (Santa Catarina)					**152.3**	[45]
	Fortaleza (Ceará)					**141.1**	[46]
	Vicosa (Minas Gerais)					8.9	[47]
	Maringa (Paraná)					47.7	[48]
	Laguna de Extremoz (Rio Gran del Norte)					**4220**	[18]
	Salvador de Bahía (Bahía)					**396** (DW) **601** (SW)	[49]
Chile	Concepción y Talcahuano (Región del Bío-Bío)	111.6	25.5	1.0			[50]
		182.0	35.2	0.9			[51]
Colombia	Medellín (Antioquía)	6.34	1.39	0.24	0.32		[52]
	Pereira (Risaralda)	50.25	2.26	1.59	1.39		[53]
	Cali (Valle del Cauca)					38.6	[54]
	Ibagué (Tolima)	68.00	28.00	74.00		**1260.00**	[55]
	Bogotá (Cundinamarca)	47.91					[56]
Costa Rica	Alajuela Puntarenas Cartago	91.31					[57]
Mexico	Cancún (Quintana Roo) Oaxaca (Oaxaca) Guadalajara (Jalisco) Tijuana (Baja California) Torreón (Coahuila)	12.14		17.00			[58]
	Ciudad de México (CDMX)	197.70	34.70			**233.00**	[59]
	Ciudad de México (CDMX)	2.18	1.39	0.95	2.33	7.95	[60]
	Valle de Tula (Hidalgo)					118.62	[61]
	Toluca (México)	22.16	33.30	35.40	55.20	124.20	[62]
Nicaragua	Boaco (Boaco)					76	[12]
	Camoapa (Boaco)					34	
	Juigalpa (Chontales)					104	
	Santo Tomás (Chontales)					85	
Uruguay	Montevideo (Montevideo)	143					[63]
	Montevideo (Montevideo)	≈ 80					[64]
Venezuela	Valencia (Carabobo)					93.23	[65]
	Maracaibo (Zulia)	32.43					[66]

Note: $CHCl_3$: Chloroform. $CHCl_2Br$: Dichlorobromomethane. $CHClBr_2$: Dibromochloromethane. $CHBr_3$: Bromoform. TTHM: Total trihalomethanes. DW: Distributed water. SW: Stored water. **Spring-summer period.

The results presented in Table 2 reveal a significant variability in the concentrations of trihalomethanes (THMs) in drinking water across Latin America. Chloroform emerges as the predominant compound in most studies [43, 48, 50, 53]. However, other THMs such as bromodichloromethane ($CHBrCl_2$), dibromochloromethane ($CHBr_2Cl$), and bromoform ($CHBr_3$) are also commonly present, with varying proportions depending on their location and water treatment conditions. TTHM levels exhibit a broad range, from very low concentrations [44, 47, 52] that comply with regulations to values exceeding the limits recommended by the WHO and national standards in some countries [18, 45, 46, 49]. Moreover, certain studies report elevated THM levels in distribution systems [50, 64] suggesting that the formation of these compounds may extend beyond initial water treatment, also occurring during transportation and storage in the network. A notable variation in brominated compound presence is observed [44, 52, 61, 62] potentially linked to bromide ion content in water sources. Overall, Table 2 highlights the complexity of the THM issue in drinking water within the region and underscores the necessity of considering the local context to implement effective control measures.

Despite the importance of trihalomethanes (THMs) as indicators of drinking water quality and their potential impact on human health, the situation in Latin America reveals significant disparities. While countries such as Argentina, Brazil, and Colombia have conducted studies on the presence of these compounds in drinking water, others, such as Honduras and the Dominican Republic, lack any studies on this matter. This imbalance highlights the urgent need to expand research coverage across the region. The situation becomes even more concerning when considering that, although some countries have established regulations governing the maximum permissible levels of THMs in drinking water, there is not always a direct correlation between the existence of such regulations and the implementation of studies assessing the actual levels of these compounds in drinking water. For instance, Ecuador and El Salvador have specific regulations but have not conducted studies to evaluate the concentration of THMs in water distributed to the population. These regulations set maximum limits that, while partially aligned with international standards, such as those of the WHO, could benefit from more substantial scientific support based on local evidence.

Moreover, some countries in the region, such as Peru and Bolivia, are even more disadvantaged, as they lack regulations and studies on the presence of THMs in drinking water. This represents a significant public health protection gap, as the population exposure to these compounds remains unknown. This could heighten the risk of associated diseases, such as bladder cancer and reproductive problems which have been linked to prolonged exposure to THMs and limit the implementation of effective mitigation strategies. In this context, it is crucial to promote both the generation of scientific data, and the development of regulations based on local evidence to ensure adequate public health protection.

Delving into this regional issue, the disparity in research and regulation is also evident in intermediate cases such as Guatemala and Panama. Although these countries have conducted studies on THMs, their research has been disseminated predominantly through journals indexed in DOAJ (Directory of Open Access Journals) which may impact their visibility and influence within the international scientific community. Nonetheless, these studies provide valuable insights into the local situation: in Guatemala, the findings are concerning, with two out of three water sources analyzed exceeding USEPA limits [67] whereas in Panama, despite levels remaining within international standards, a discrepancy exists between the national regulatory limits and EPA standards [67]. These cases highlight the importance of conducting studies aligning national regulations with international standards and ensuring the broad dissemination of results to facilitate public health decision-making.

To facilitate the visualization of regional disparities in the monitoring and regulation of THMs, the data presented in Tables 1 and 2 has been consolidated into Figure 1. This figure illustrates that countries such as Brazil, Colombia, Mexico, and Chile stand out for having both regulatory frameworks and studies (depicted in green). In contrast, Peru and Bolivia (in red) exhibit the most critical situation due to the absence of both elements. Guatemala and Panama (represented by green diagonal stripes) have conducted studies published in DOAJ but lack regulations. Countries like Ecuador and El Salvador (in orange) have regulations but no published studies, while Argentina, Paraguay, and Uruguay (in yellow) have conducted studies without specific regulations. This scenario reveals a distinct geographic and socioeconomic pattern, where larger, more resource-rich countries tend to have a more comprehensive framework for THM control and study. In contrast, smaller or resource-constrained nations show varying degrees of progress in this matter.

4.3. Actions to Eliminate THMs in Drinking Water

To reduce or eliminate THMs in potable water, it is crucial to optimize the disinfection process by reducing chlorine doses and avoiding chlorination at multiple points while also controlling contact time and Ph [12, 66]. Prioritizing the removal of THM precursors is essential, using technologies such as nanofiltration, activated carbon, and enhanced coagulation to eliminate natural organic matter [12, 48, 61]. Alternative disinfectants like chlorine dioxide, chloramines, or ozone may also be employed, but their lack of residual effects should be considered [61].

Protecting water sources from contamination and optimizing the distribution network, including regular pipe maintenance and reducing water residence time, are essential [50, 54, 55]. Continuous monitoring of THMs and adapting control strategies to local conditions are imperative [56, 64]. Combining these actions, tailored to specific contexts, is the most effective way to ensure water quality and minimize health risks [57].

4.4. Methodologies Employed in THMs Quantification

Advances in microextraction techniques for analyzing THMs in Latin America have revolutionized their detection in drinking water by offering methodologies that enhance efficiency, sensitivity, and environmental sustainability. The evolution from traditional liquid-liquid extraction to modern techniques such as headspace solid-phase microextraction (HS-SPME), hollow fiber sorptive bar microextraction (HF-SBME), and single-drop microextraction (SDME) has significantly reduced analysis times. For instance, Correa, et al. [68] achieved extractions in just 5 minutes using HF-SBME, while Vallejo-Vargas, et al. [53] optimized an HS-SPME protocol with 20 minute-extraction times.

A significant advantage of these modern techniques is their ability to significantly reduce or eliminate the use of organic solvents, as highlighted by Aguirre-González, et al. [69]; Rosero, et al. [70] and Carlos, et al. [71]. This not only minimizes environmental impact but also lowers occupational risks associated with handling toxic substances. Concurrently, these methodologies have achieved exceptional sensitivity levels, allowing THMs to be quantified at concentrations as low as ng/L to µg/L. Noteworthy results include those of Rosero, et al. [70] who demonstrated detection limits for hollow fiber liquid-phase microextraction (HFLPME) ranging from 0.018 µg/L to 0.049 µg/L, and Correa, et al. [68] who reported 0.017–0.037 ng/mL detection limits using HF-SBME.

The optimization of these techniques has required meticulous adjustment of multiple experimental parameters. Aguirre-González, et al. [69] demonstrated the superiority of the carboxen/polidimetilsiloxane fiber (75 µm) for HS-SPME and, together with Vallejo-Vargas, et al. [53] established optimal extraction temperatures. Vallejo-Vargas, et al. [53] also optimized the desorption temperature at 250°C. Studies by Aguirre-González, et al. [69]; Duarte, et al. [72] and Vallejo-Vargas, et al. [53] explored the optimization of extraction and desorption times, further demonstrating the positive impact of adding NaCl on extraction efficiency. Vallejo-Vargas, et al. [53] complemented these findings by establishing additional optimal conditions: a 2 mL sample volume and a 200 rpm agitation speed.

Figure 1.
Geographical distribution of the status of regulations and studies on trihalomethanes in drinking water in Latin American countries.

The validation of these optimized methodologies has been conducted through the analysis of real potable water samples, allowing for a precise evaluation of THM levels in distribution systems. Vallejo-Vargas, et al. [53] implemented his method to analyze drinking water in Pereira, while Aguirre-González, et al. [69] applied it to a Colombian treatment plant. Correa, et al. [68] also validated his methodology with real samples. In a comparative study, Rosero, et al. [70] demonstrated the superior analytical sensitivity of HFLPME.

These methodological innovations have resulted in analytical protocols that combine speed, sensitivity, efficiency, and environmental sustainability to determine THMs in water. These protocols serve as fundamental tools for monitoring the quality of drinking water and protecting public health.

4.5. Alternative or Combined Disinfection Methods with Chlorination

To understand this, strategies have been developed to minimize the presence of disinfection by-products (DBPs) in drinking water. Removing natural organic matter (NOM) prior to disinfection has proven to be an effective strategy, using techniques such as coagulation/flocculation with natural tannins [48] ion-exchange resins [73] and granular activated carbon

(GAC) [74]. Although GAC is effective, it may not control the formation of all DBPs. Optimization of disinfection processes, including the use of lower chlorine doses and alternative disinfectants such as chloramine, ozone, or UV radiation, has also been explored [61, 75-77].

In addition, adsorbent materials such as sugarcane bagasse, coconut mesocarp, and hexadecyltrimethylammonium (HDTMA)-modified zeolite have been investigated for the removal of formed THMs[77, 78]. HDTMA-modified zeolite has shown efficacy due to creating a hydrophobic phase that attracts these compounds [77]. Pretreatment of water, such as coagulation, flocculation, and sedimentation (C/F/S) prior to filtration, is crucial for removing DBP precursors, and natural coagulants like Moringa oleifera (MO) are suitable substitutes for chemical coagulants [74].

Finally, research has highlighted how environmental factors, such as algae and bromide, and operational factors, such as pH [76] and contact time, influence DBP formation. This knowledge allows treatment plants to adapt their processes to minimize DBP formation. Research on DBP formation and control has improved the understanding of these compounds, enabling the development and enhancement of water treatment technologies to ensure a safer water supply for the population.

4.6. Future Actions

It is important to promote future actions that are focused on processes for obtaining safe water, as well as improvement in safe storage, sanitation and hygiene practices. Currently, these principles are being promoted by various institutions such as the Center for Disease Control and Prevention (CDC) and the Pan American Health Organization and non-governmental organizations (NGOs), such as Population Service International (PSI) and CARE. Analysis of the general state of chlorination practice in several Latin American countries shows that, although the use of chlorine is widely known and considered a conventional disinfection method by health care agencies, its application in homes is not necessarily effective. Additionally, there is a lack in adequate disinfection practice, in order to avoid subsequent risks, as well as compliance actions in medium and long-term follow-up. More research needs to be done and solutions found to address the effective implementation of disinfection processes at urban and rural levels.

5. Conclusions

This study provides a comprehensive assessment of trihalomethane (THM) contamination in Latin American drinking water, encompassing a review of existing regulations, reported THM levels, and analytical methodologies. The findings reveal significant regional disparities in regulatory frameworks, research activity, and THM concentrations. While some countries have implemented relatively stringent regulations and more extensive monitoring data, others lack adequate regulations, data, or both. The reported THM levels vary considerably, with some instances exceeding World Health Organization (WHO) guideline values, raising concerns about potential health risks for exposed populations.

5.1. Implications

The observed variability in regulatory frameworks across Latin American countries highlights the need for greater harmonization of THM standards. While complete uniformity may not be feasible or desirable due to local conditions, adopting a common framework based on international best practices, such as the WHO guidelines, could improve public health protection. Furthermore, many countries must strengthen their existing regulations by including specific limits for individual THMs, updating outdated standards, and enhancing enforcement mechanisms.

The scarcity of data on THM levels in many countries underscores the urgent need to establish or expand systematic monitoring programs. These programs should prioritize areas with known or suspected high THM levels, utilize standardized analytical methods, and ensure data quality and accessibility.

5.2. Limitations

The study relied primarily on publicly available data from scientific publications and government websites. Data from some countries were limited, outdated, or inaccessible, which may have impacted the completeness of the analysis.

The study used maximum values, which represents a worst-case scenario.

5.3. Future Research

Conduct detailed investigations into the characteristics of NOM in Latin American water sources and their reactivity with chlorine to better understand the factors driving THM formation in different contexts. Undertake epidemiological studies in Latin America to assess the potential health impacts of THM exposure, considering different exposure routes and vulnerable populations.

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