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Assessing Rainwater Quality Across Regions in Thailand: Implications for Public Health and Water Management

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Abstract

Background: Recognizing the impact of contaminated water on public health, ensuring access to high-quality water is critical for improving health outcomes. Rainwater, a significant natural resource in Thailand, exhibits varying compositions across regions, directly influencing overall water quality and consequently affecting public health. Therefore, there is a need to conduct comprehensive surveys to assess rainwater suitability for household use.

Purpose: This study aimed to survey the quality of rainwater in Thailand by determining the composition as physical, chemical and biological in accordance with the Department of Health Guidelines for Drinking Water Quality (2020) of Thailand.

Methods: From November 2022 to February 2024, 152 rainwater samples were collected from six regions: north, northeast, central, east, southern east coast, and southern west coast of Thailand. The water analysis followed the Standard Methods for the Examination of Water and Wastewater (23rd edition). Descriptive statistics were applied to analyze data across 82 parameters, including 21 criteria aligned with the Guidelines for Drinking Water Quality and 61 parameters focusing on pesticide substances.

Results: A comprehensive analysis of the 152 rainwater samples revealed that every sample exhibited at least one parameter failing to meet water quality standards. Key concerns included acidic pH levels observed in 80% of samples and excessive coloration exceeding permissible limits in 20% of samples. Bacterial contamination, predominantly total coliform bacteria, was widespread, detected in approximately 87% of samples, surpassing occurrences of Escherichia coli. Mercury contamination was identified in a single sample from northeast Thailand, highlighting localized chemical risks. Pesticides, such as carbamates, organophosphates, pyrethroids, and glyphosate, were sporadically detected in the southern region. These findings underscore the urgent need to enhance and enforce water quality standards before promoting widespread consumption of rainwater.

Conclusions: A comprehensive analysis of the 152 rainwater samples revealed that every sample exhibited at least one parameter failing to meet water quality standards. Key concerns included acidic pH levels observed in 80% of samples and excessive coloration exceeding permissible limits in 20% of samples. Bacterial contamination, predominantly total coliform bacteria, was widespread.

Keywords: Rainwater, Water Quality, Qater Management

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Introduction:

Water is an essential factor for life, comprising up to two-thirds of the human body, or approximately 70%. Deprivation of water for more than three consecutive days can be seriously fatal. Global water situation reports highlight that one in five people worldwide lack access to clean water or face water scarcity. In addition, half of the world's population lacks adequate water for sanitation.(1) Over the past decade, more than 5 million people have died from diseases caused by contaminated water. The International Water Management Institute (IWMI) estimates that by 2025, 4 billion people in 48 countries (two-thirds of the global population) will face water scarcity.(2) The World Bank forecasts that in the next 30 years, half of the world's population will experience water shortages if the current extravagant water use continues.(3) The United Nations (UN) predicts that by 2030, global freshwater demand will exceed supply by 40%, driven by climate change, human activities, and population growth.(1)

Global water scarcity become one of the main problems reported by UN as over a billion people currently suffer from water scarcity, and another 2.7 billion people experience water shortages at least one month annually. In a 2014 survey of 500 cities worldwide, one in four was found to be in a water-stressed situation. Cape Town, South Africa, is projected to be the first major city to face water shortage issues due to three consecutive years of low rainfall and increasing population demand. By 2030, 11 cities, including São Paulo (Brazil), Bangalore (India), Beijing (China), Cairo (Egypt), Jakarta (Indonesia), Moscow (Russia), Istanbul (Turkey), Mexico City (Mexico), London (England), Tokyo (Japan), and Miami (USA), are expected to face water scarcity. Australia, the driest continent, faces inconsistent rainfall, leading to the development of desalination plants. Australian researchers and international teams are working on eco-friendly and energy-efficient desalination systems to alleviate freshwater scarcity. Currently, half of the freshwater used in Australia's major cities comes from desalination plants.(1)

The Sustainable Development Goals (SDGs), specifically Goal 6, aim to ensure availability and sustainable management of water and sanitation for all by 2030. Section 6.1 aims to achieve universal and equitable access to safe and affordable drinking water, while Target 6.3 focuses on improving water quality by reducing pollution, eliminating dumping, minimizing the release of hazardous chemicals and materials, and significantly reducing untreated wastewater by half, increasing recycling and safe reuse globally by 2030. The SDGs also emphasize the importance of integrated water resources management at all levels, including transboundary cooperation as appropriate, under Section 6.5. Effective water management requires coordinated development and management of water, land, and related resources to maximize economic and social welfare equitably without compromising the sustainability of vital ecosystems. This approach is crucial for addressing the multifaceted challenges of water scarcity, which often extend beyond national borders.(4) By 2030, countries are encouraged to implement integrated water resources management (IWRM) strategies that consider the needs of all users, including agriculture, industry, and households, while maintaining the ecological balance of water sources.(5) Another critical component of Goal 6 is Section 6.4, which aims to substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity. Enhancing water-use efficiency is vital for sustaining agricultural productivity, industrial growth, and urban development, especially in regions experiencing rapid population growth and climate change impacts. Innovations in irrigation technologies, wastewater treatment, and water recycling are essential for optimizing water use. Additionally, promoting practices such as rainwater harvesting, greywater reuse, and the use of drought-resistant crops can significantly reduce water demand and mitigate the effects of water scarcity. Collectively, these efforts contribute to a more resilient water supply system capable of supporting both human and environmental health in the long term.(4)

Rainwater is a natural source of freshwater that replenishes both surface and groundwater supplies. Groundwater constitutes 30.1% of the world's freshwater, while surface water, including

rivers and lakes, makes up only 0.3%. The remainder is stored in ice caps, glaciers, and snow, accounting for 68.7% of the world's freshwater. Thailand, located in Southeast Asia's tropical region, experiences two monsoon seasons: the southwest monsoon (mid-May to mid-October) and the northeast monsoon (November to mid-December). Over the past decade (2011-2020), Thailand's average annual rainfall ranged from 1,343 mm to 2,017 mm, with 2019 recording the lowest and 2017 the highest. Rainwater can be harvested for various uses, but its quality, particularly for consumption, must meet public health standards.(6) While rainwater harvesting is increasingly recognized as a viable solution to augment water supplies in regions experiencing water stress, traditional methods of collecting and storing rainwater, such as the use of large jars and ponds, have been employed for centuries and thus require modern advancements in rainwater harvesting technologies, including rooftop catchment systems and advanced filtration methods. These systems do not only further enhance the ability to capture and utilize rainwater for various purposes, they also can provide a supplementary water source for domestic use, irrigation, and industrial processes, reducing dependence on conventional water sources and alleviating pressure on over-exploited groundwater reserves.

However, the effectiveness and safety of rainwater harvesting depend significantly on the quality of the collected rainwater. Atmospheric pollutants, such as particulate matter, heavy metals, and biological contaminants, can adversely affect the quality of rainwater, making it unsuitable for direct consumption without proper treatment. Therefore, it is crucial to implement stringent monitoring and treatment protocols to ensure that harvested rainwater meets public health standards.(7) Rainwater, a part of the water cycle, is generally clear and colorless but can dissolve gases and react with pollutants in the atmosphere. Rain falling through polluted air may contain contaminants, chemicals, and pathogens. Acid rain, caused by sulfur dioxide (SO2) and nitrogen oxides (NOx) from fossil fuel combustion, reacts with water to form sulfuric acid (H2SO4) and nitric acid (HNO3). A 2010 Pollution Control Department report found that rainwater in six Thai monitoring stations had pH levels between 4.6 and 5.(8, 9) In 2020, the Environmental Office of Nakhon Sawan Province reported that rainwater generally met the World Health Organization (WHO) standards, except for coliform bacteria levels.(10) Studies have shown that with appropriate filtration and disinfection processes, rainwater can be a reliable and safe source of drinking water. Promoting the adoption of rainwater harvesting, coupled with robust water quality management practices, can play a pivotal role in addressing water scarcity and ensuring sustainable water resources management in Thailand and other regions with similar climatic conditions. Rainwater harvesting could serve as an alternative or supplementary water source for communities globally and in Thailand. While meteorological stations across Thailand monitor rainfall, comprehensive nationwide quality assessments are lacking. This research, involving the Meteorological Department, Ministry of Digital Economy and Society and the Department of Health, Ministry of Public Health, aims to study rainwater quality, including physical, chemical, and biological parameters, and analyze pesticide residues. This initiative highlights the importance of rainwater as a sustainable water source for the future.

Research Methodology

To comprehensively evaluate the suitability of rainwater as a viable source of potable water in Thailand, the research team strategically selected 152 meteorological stations to represent 1,200 meteorological stations countrywide for the collection of rainwater samples. The rainwater samples were collected from 139 meteorological stations operated by the Thai Meteorological Department, 12 public health centers (Centers of Health), and one sample from the Institute of Urban Well-being. The sampling period spanned from November 2022 to February 2024. This timeframe ensured the inclusion of various seasonal effects on rainwater quality. The stations were strategically distributed across 70 provinces out of the 77 provinces in Thailand, ensuring comprehensive national coverage, which

include provinces such as Chiang Mai, Chiang Rai, Mae Hong Son, Nan, Lampang, Lamphun, Phayao, Phetchabun, Phitsanulok, Sukhothai, Uttaradit, Kamphaeng Phet, Tak, Phichit, Loei, Bueng Kan, Nong Khai, Sakon Nakhon, Nakhon Phanom, Udon Thani, Ubon Ratchathani, Khon Kaen, Chaiyaphum, Kalasin, Mukdahan, Maha Sarakham, Si Sa Ket, Roi Et, Buri Ram, Yasothon, Surin, Nong Bua Lamphu, Amnat Charoen, Nakhon Ratchasima, Nakhon Sawan, Chai Nat, Uthai Thani, Lopburi, Saraburi, Pathum Thani, Suphan Buri, Kanchanaburi, Ratchaburi, Nakhon Pathom, Bangkok, Samut Songkhram, Samut Prakan, Chachoengsao, Nakhon Nayok, Prachinburi, Chonburi, Rayong, Chanthaburi, Trat, Sa Kaeo, Prachuap Khiri Khan, Chumphon, Surat Thani, Nakhon Si Thammarat, Phatthalung, Songkhla, Yala, Pattani, Narathiwat, Ranong, Phang Nga, Phuket, Krabi, Trang, and Satun. This extensive sampling effort was designed to create a comprehensive dataset that would serve as a foundational database for future research and development, highlighting the potential of rainwater as a consumable resource. This study is pioneering in its scope, as it is among the first to gather rainwater data across a wide geographical expanse, encompassing diverse regions to accurately capture variations in rainwater quality throughout the country.

Upon collection, the rainwater samples were subjected to rigorous laboratory testing to determine their suitability for consumption. The analysis focused on three key areas: physical, chemical, and biological quality, referencing the 2023 drinking water standards set by the Department of Health. The physical analysis included parameters such as turbidity, color, and suspended solids. The chemical analysis encompassed a wide range of contaminants, including heavy metals, pH levels, and the presence of harmful chemicals. The biological analysis assessed the presence of coliform bacteria and other pathogenic microorganisms. Additionally, the study analyzed the presence of pesticide residues, specifically targeting four groups of pesticides: Carbamates, Organophosphates, Organochlorines, and Pyrethroids. Given the widespread use of pesticides in agriculture, the study also tested for two commonly used herbicides: Glyphosate and Paraquat. These substances were chosen due to their prevalence in agricultural runoff, which can contaminate rainwater. The detection of these chemicals was conducted using advanced laboratory techniques to ensure precise and accurate results. This comprehensive analysis aimed to provide a detailed understanding of the rainwater's quality and its potential as a safe drinking water source for households and communities in Thailand.

By evaluating the rainwater quality against established drinking water standards, this research seeks to highlight the potential of rainwater harvesting as a sustainable solution to water scarcity. The findings from this study will contribute to the development of policies and practices that promote the safe and efficient use of rainwater, ensuring a reliable and clean water supply for future generations.

Data Analysis

From November 2022 to February 2024, 152 rainwater samples were collected from six regions: north, northeast, central, east, southern east coast, and southern west coast of Thailand. The water analysis followed the Standard Methods for the Examination of Water and Wastewater (23rd edition). Descriptive statistics were applied to analyze data across 82 parameters, including 21 criteria aligned with the Guidelines for Drinking Water Quality and 61 parameters focusing on pesticide substances.

Results

Comprehensive Overview of Rainwater Sample Collection

The study on rainwater quality in Thailand, encompassing a broad geographic scope with 152 samples from 70 out of 77 provinces, provides valuable insights into the country's potable water quality. These samples, analyzed according to the Department of Health's 2020 potable water quality standards, reveal significant regional and temporal variations in water quality. The study's findings underscore the need for continuous monitoring and targeted interventions to ensure safe drinking water across all regions.

Regional Variations in Rainwater Quality

The distribution of samples across the six regions, as defined by the Meteorological Department, showed significant discrepancies in sample collection and quality. The Northeast region, with the highest number of samples (40), followed by the Eastern Southern region (34) and the Northern region (32), reflects the regional variations in rainfall patterns, population density, and logistical feasibility of sample collection. The Western Southern region, with only eight samples, highlights the need for more extensive sampling to obtain a comprehensive understanding of water quality in less represented areas. Figure 1 illustrates the locations of the sampling sites, while Figure 2 presents Number of Rainwater Samples Categorized by the Meteorological Department's Regions, respectively.

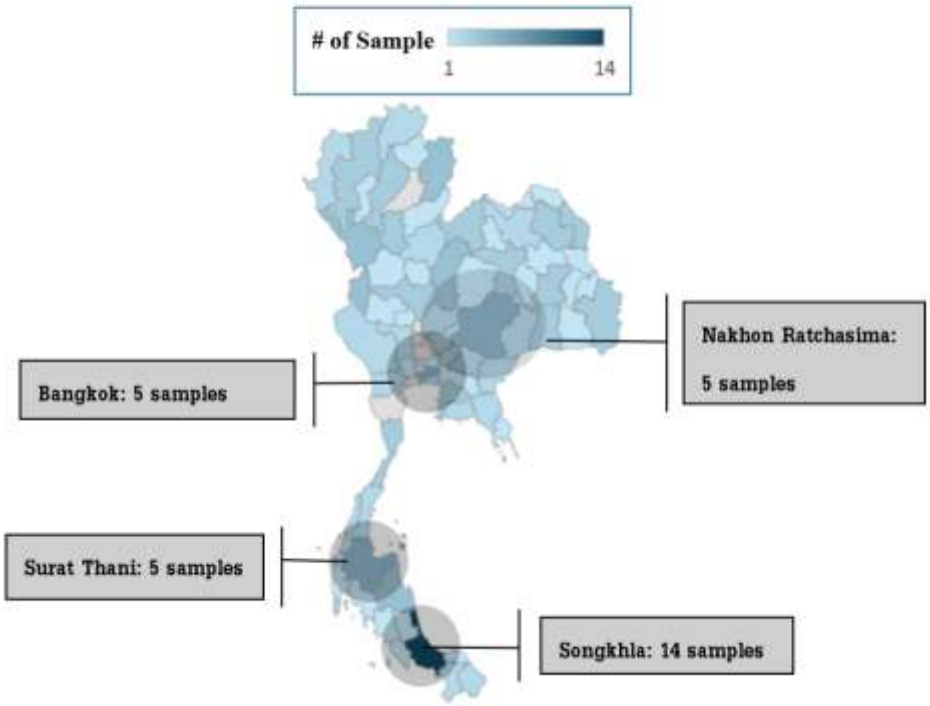


Figure 1. An overview where rainwater samples were collected in each province

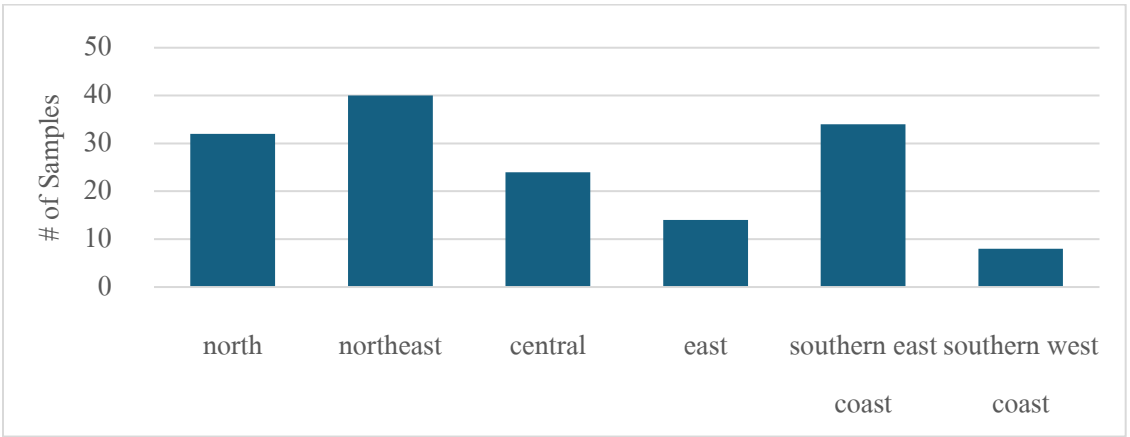


Figure 2. Number of rainwater samples in 6 regions categorized by the meteorological department

The timing of sample collection, aligned with the varying rainy seasons, provides crucial context for understanding the seasonal impact on water quality. For instance, the Northern region's samples, collected from May to October, and the Southeastern region's samples, collected from December to February, highlight the influence of seasonal rainfall on water quality. This temporal variability is essential for capturing representative data and identifying seasonal trends in water quality.

Chemical Contaminants in Rainwater

The chemical analysis of rainwater samples revealed a low incidence of contamination, with only a few samples containing detectable levels of specific compounds. Fenobucarb, an insecticide from the carbamate group, was found in one sample from the Central region at a concentration below 0.1 µg/L. The presence of Fenobucarb, although minimal, suggests that regulatory controls are effective but require ongoing enforcement to prevent contamination.

Organophosphate compounds, including Triazophos and Profenofos, were detected in two samples from the Northern and Southeastern regions, respectively, both at concentrations below 0.1 µg/L. This finding highlights the need for continuous monitoring and stricter regulations on pesticide use to mitigate potential health risks associated with organophosphates.

Pyrethroids, detected in three samples, with Cypermethrin in the Northern and Southeastern regions and Permethrin in the Southeastern region, also at concentrations below 0.1 µg/L, underscore the ongoing risk of pesticide contamination. These findings suggest that agricultural practices involving pyrethroids need careful management to prevent water contamination.

Glyphosate and Paraquat, herbicides commonly used in agriculture, were found in the Southeastern region in the forms of AMPA and Glyphosate, both at concentrations below 5.0 µg/L. The detection of these herbicides indicates the need for sustainable agricultural practices and effective management of herbicide application to protect water quality.

The absence of organochlorine compounds, a class of persistent organic pollutants, in all samples is a positive outcome, reflecting the effectiveness of regulations banning or limiting the use of these harmful chemicals. This finding highlights the success of regulatory measures in reducing the presence of these dangerous compounds in the environment.

In summary, the chemical analysis, pesticide substances, revealed a low incidence of contamination. Carbamate compounds, Fenobucarb was found in 1 sample from the Central <0.1 µg/L. Organophosphate compounds, including Triazophos and Profenofos, were detected in 2 samples from the Northern and Eastern Southern <0.1 µg/L. Pyrethroids, detected in 3 samples, with Cypermethrin in the Northern and Eastern Southern and Permethrin in the Eastern Southern <0.1 µg/L. Glyphosate and Paraquat were found in the Eastern Southern region in the forms of AMPA and Glyphosate <5.0 µg/L. (Figure 3)

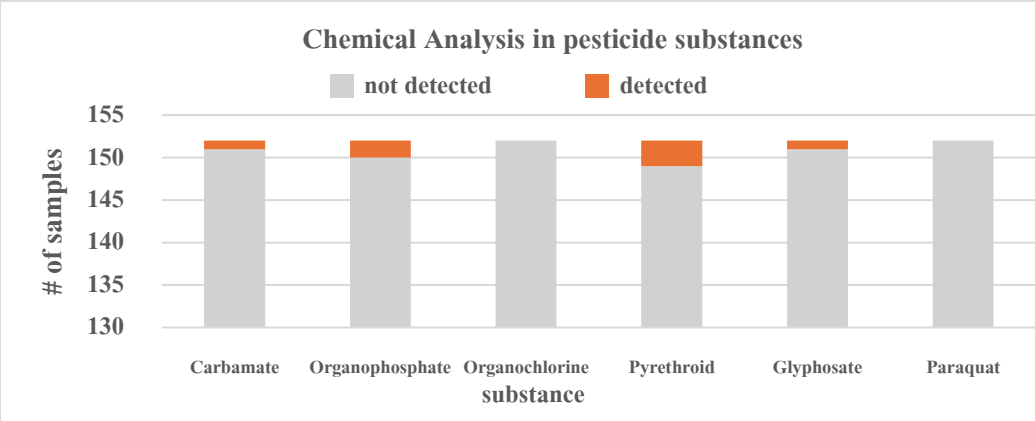


Figure 3. Number of rainwater samples in each substance

Physical Quality Parameters

The physical quality of rainwater samples, assessed based on turbidity, apparent color, and pH, provides critical insights into water clarity and safety.

Turbidity, a measure of water clarity, is an important parameter as high turbidity can indicate the presence of contaminants and affect the disinfection process. According to the standards, turbidity must not exceed 5 NTU. The categorization of turbidity levels into color codes (green: 0.01-4.49 NTU, yellow: 4.50-5.00 NTU, red: >5.00 NTU) provides a clear framework for assessing water quality. The analysis revealed that all 152 samples met the turbidity criteria, indicating overall clear rainwater. However, the Eastern Southern region's categorization into the yellow group suggests that while turbidity levels are within acceptable limits, they are close to the threshold and require ongoing monitoring.

Apparent color, indicating water discoloration, must not exceed 15 Pt/Co units. The samples were categorized into four groups based on their apparent color: blue (not detected), green (0.01-13.49 Pt/Co), yellow (13.50-15.00 Pt/Co), and red (>15.00 Pt/Co). The analysis showed that 39 samples did not meet the apparent color criteria, with values exceeding 15 Pt/Co, and the highest recorded value of 51.87 Pt/Co from the Northeast region. Additionally, eight samples fell into the yellow category. These findings highlight the need for interventions to address sources of discoloration, such as agricultural runoff and industrial effluents.

The pH of drinking water must be within the range of 6.50 to 8.50. The pH values were categorized into three groups: green (7.16-7.84), yellow (6.50-7.15 or 7.85-8.50), and red (<6.50 or >8.50). The analysis indicated that only 29 samples met the pH criteria, with all samples from the Eastern region failing to meet the standard. This significant deviation highlights the need for targeted interventions to address pH imbalances, as water with pH outside the acceptable range can pose health risks and affect disinfection efficacy.

The assessment results were categorized into three groups as shown in figure 4 to classify the overall quality including green, yellow and red. In each category based on three key parameters: turbidity, apparent color, and pH. Green group represented rainwater samples that passed all three parameters. This indicated that the water was of good physical quality. Yellow group included samples that passed two out of the three parameters. The water's physical quality was considered acceptable. Red group was for samples that passed only one or none of the three parameters. These results suggested that the rainwater was of poor physical quality and did not meet the standards for physical quality parameters.

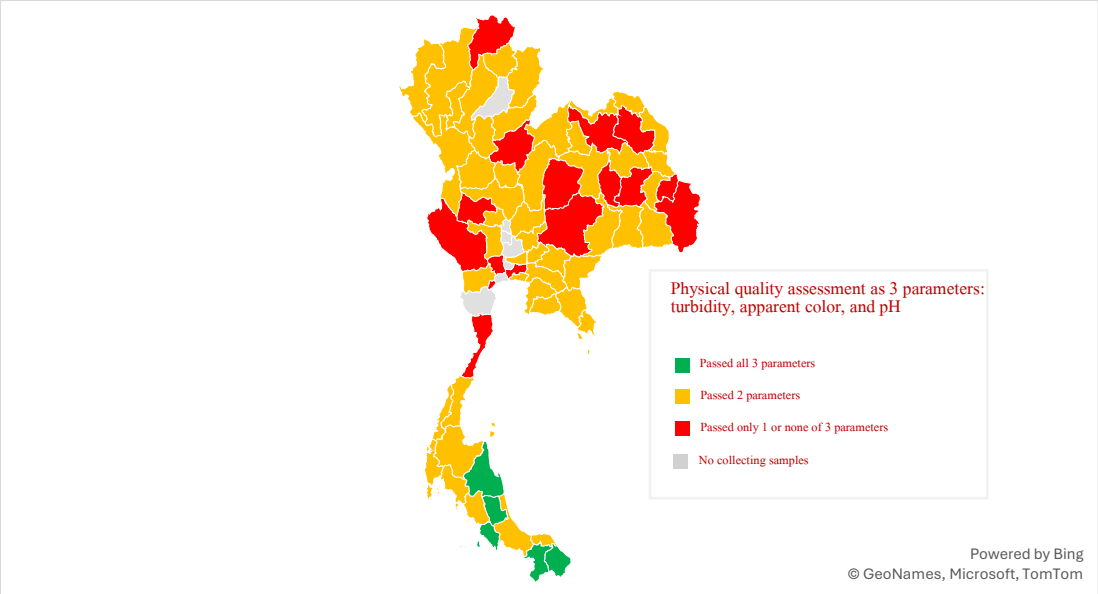
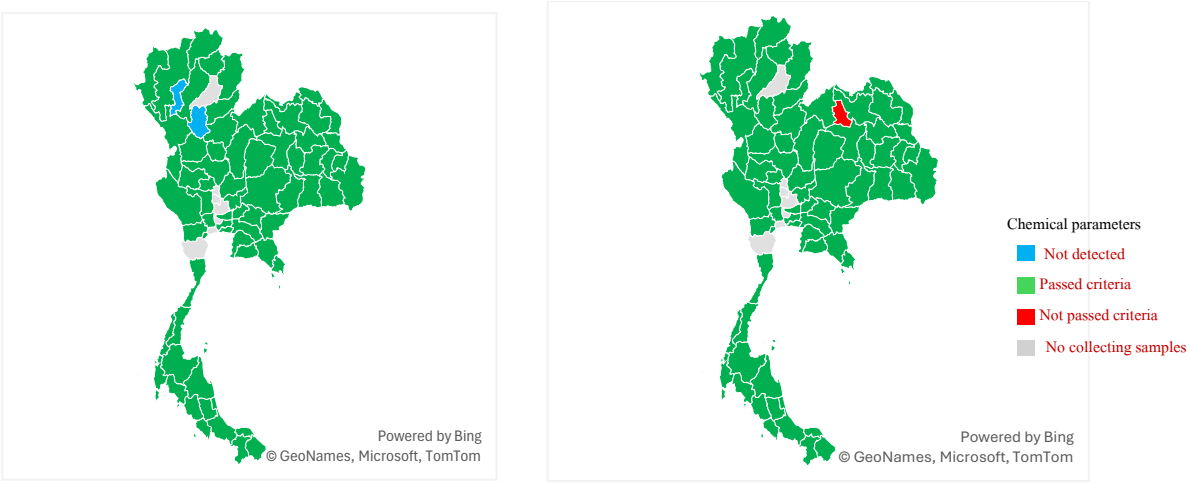


Figure 4. The physical quality assessment results of water, classified by the levels: Green, Yellow, and Red.

The general chemical water quality assessment, covering seven parameters Total Dissolved Solids (TDS), Hardness as CaCO3, Sulfate, Chloride, Nitrate as NO3, Nitrite as NO2, and Fluoride revealed that only four samples were free of all seven substances, classified in the blue group (Figure 5a). Sulfate was the most frequently detected substance, found in 130 samples. This widespread presence of sulfate indicates potential sources of contamination, such as industrial discharges and agricultural runoff, necessitating effective management strategies to control these pollutants. The Heavy Metals assessment, including Iron, Manganese, Copper, and Zinc were free of all. The Toxic Heavy Metals, including Lead, Chromium, Cadmium, Arsenic, and Mercury-revealed that only 1 sample found Mercury in Northeastern region, classified in the red group. (Figure 5b) Based on the above data, the categorization of chemical water quality levels can be presented in a map of Thailand, as shown in Figures 5.



(a) general chemical parameters (b) toxic heavy metal parameters

Figure 5. Chemical water quality levels assessment in provinces

The bacteriological Quality of Rainwater is assessed based on two parameters: Total Coliform Bacteria and Escherichia coli (E. coli). According to the standard, both parameters must be absent in 100 milliliters of water, or present at less than 1.1 MPN per 100 milliliters. Analysis of 152 rainwater samples collected from different regions of the country revealed the following:

Total Coliform Bacteria: compared with the quality standards set by the Department of Health, total coliform bacteria were detected in all regions. The highest exceedance rate was observed in the Central region and the Western South, where 100% of samples exceeded the standard. This was followed by the Eastern region (92.86%), the Northern region (90.62%), and the Eastern South (88.24%). The lowest exceedance rate was found in the Northeastern region (70.00%). Overall, only 20 samples (13.16%) met the standard, while 132 samples (86.84%) exceeded the permissible limit.

Escherichia coli (E. coli): E. coli was also detected in rainwater samples from all regions. The highest rates of exceedance were recorded in the Western South (75.00%), Eastern South (70.59%), and the Northern region (46.87%). In contrast, the Northeastern and Central regions showed exceedance rates of 37.50%, while the Eastern region had the lowest at 28.57%. In total, 79 samples (51.97%) met the standard, while 73 samples (48.03%) exceeded it.

In summary, when considering the overall bacteriological quality of rainwater, total coliform bacteria were found to exceed the standard more frequently than E. coli, as presented in Table 1.

Table 1. Bacteriological Quality of Rainwater by Meteorological Regions

Region Rainwater Samples	Total coliforms bacteria				Escherichia coli			
	Met Standard		Exceeded Standard		Met Standard		Exceeded Standard	
	n	%	n	%	n	%	n	%
Northern	3	9.38	29	90.62	17	53.13	15	46.87
Northeastern	12	30.00	28	70.00	25	62.50	15	37.50
Central	0	0	24	100	15	62.50	9	37.50
Eastern	1	7.14	13	92.86	10	71.43	4	28.57
Southern (East Coast)	4	11.76	30	88.24	10	29.41	24	70.59
Southern (West Coast)	0	0	8	100	2	25.00	6	75.00
Total	**20**	**13.16**	**132**	**86.84**	**79**	**51.97**	**73**	**48.03**

Based on the bacteriological assessment of rainwater across both parameters, the results were categorized into three quality levels:

- Green Level: Samples that met the quality standard for both total coliform bacteria and *E. coli*.
- Yellow Level: Samples that met the quality standard for only one parameter.
- Red Level: Samples that failed to meet the quality standard for both parameters.

The distribution of bacteriological rainwater quality across regions is illustrated in Figure 6.

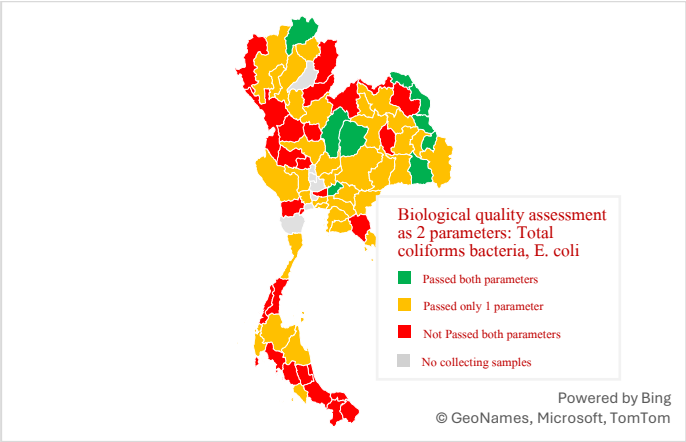


Figure 6 Biological water quality assessment in provinces

Discussion

From a total of 152 rainwater samples collected nationwide, differences were observed in both the sampling periods and the number of samples gathered across regions. These variations were largely attributable to differences in local climatic conditions and rainfall patterns. In some areas, insufficient rainwater was available for collection, making it difficult to obtain adequate volumes for laboratory analysis of chemical constituents and other quality parameters. Consequently, the limited sampling timeframe directly affected the volume of rainwater available for examination.

Testing rainwater for pesticide residues revealed the presence of contaminants in only a small number of samples, typically between one and three for each type of chemical detected. The pesticide groups identified included organophosphates, pyrethroids, carbamates, and glyphosate. Organophosphates—phosphorus-based organic compounds—are widely used as ingredients in household and industrial products, most often in spray formulations for pest and insect control. Their popularity stems from their low cost, high effectiveness, and short environmental persistence, typically degrading within one to two

weeks. However, frequent application can lead to residual accumulation in soil, water, and air (11). In this study, organophosphates were primarily detected in the Northern region, characterized by extensive rice farming, and in the Eastern South, an area dominated by plantation agriculture such as rubber, oil palm, durian, and rambutan (12). Importantly, no organochlorine pesticides (e.g., DDT), known for their persistence and long-term accumulation, were detected in any of the 152 rainwater samples.

Pyrethroids were detected in the Northern region, where upland crops and fruit orchards are cultivated, and in the Eastern South, where both rice farming and perennial crop cultivation are common (12). Carbamates, another group of insecticides used in modern agriculture, were detected in only one sample from the Central region, an area where around 40% of land use is dedicated to crop farming (rice and maize) and livestock production. Glyphosate, a foliar-applied herbicide restricted to crops such as sugarcane, rubber, oil palm, cassava, maize, and fruit orchards, was detected in only one sample from Nakhon Si Thammarat Province, a major agricultural hub for these crops.

Although pesticide residues were detected, the findings represent only a limited number of rainwater samples from certain regions. Many areas sampled are not major agricultural zones, which may explain the absence of detectable residues. Further studies should therefore target agricultural areas more systematically and increase sample sizes to strengthen comparisons and assess the influence of environmental and geographical factors on rainwater quality (12).

Thus, when compared with Drinking Water Standards, rainwater quality was evaluated against the Department of Health's 2020 drinking water standards (13), considering three categories: (1) physical quality, (2) general and heavy-metal chemical quality, and (3) bacteriological quality. Overall, most rainwater samples failed to meet standards for pH (acidity/alkalinity) and bacteriological quality. Only one sample failed in terms of toxic heavy metals, specifically mercury, which exceeded the permissible limit in a sample collected from Nong Bua Lamphu Province.

Physical parameters assessed included turbidity, apparent color, and pH. As rainwater samples were collected directly in open air (not via rooftops, gutters, or ground surfaces), turbidity levels were generally low, ranging between 0.18–4.78 NTU. This aligns with previous studies suggesting that turbidity issues often arise from the use of rooftops and storage containers as collection systems (14). Apparent color exceeded standards in 50% of samples, likely influenced by airborne dust and particulates. In central Thailand, for example, dense urbanization, heavy traffic, and industrial activity contribute to high levels of air pollutants throughout the year, which may affect rainwater quality. In northern Thailand, haze from agricultural burning and forest fires was a significant factor.

pH values indicated that rainwater in the Central and Eastern regions was more acidic than in other areas. This can be attributed to atmospheric pollution from fossil fuel combustion, particularly sulfur dioxide and nitrogen oxides. Even in non-industrial regions, natural processes—such as the dissolution of atmospheric carbon dioxide into raindrops, forming carbonic acid—contribute to natural rainwater acidity, typically within a pH range of 5.6–5.7 (14). These findings suggest that pH thresholds should be reassessed or treatment measures considered before rainwater is used for consumption.

General chemical quality parameters, including total dissolved solids (TDS), hardness, sulfates, chlorides, nitrates, nitrites, and fluoride, were detected in small amounts but remained within permissible limits. The maximum TDS recorded was 261 mg/L, well below the standard threshold.

Heavy metals were detected only at trace levels, far below health-based standards. This was possible due to the use of high-sensitivity laboratory methods. Such metals are naturally occurring but can also originate from human activities, such as agriculture and industrial processes such as mining, petrochemicals, tanning, and paint production (15). In southern

Thailand, where large-scale plantations and associated industries such as rubber and palm oil processing are concentrated, atmospheric pollutants may explain the presence of low-level heavy metals in rainwater (16). While these levels did not exceed standards, long-term accumulation in the human body can pose health risks. Mercury exceedance in Nong Bua Lamphu Province is of particular concern, as the area is heavily dedicated to sugarcane farming and is geographically surrounded by mountains, which may facilitate the accumulation of agricultural chemicals in the environment (17).

Bacteriological analysis revealed that most samples failed to meet the standards, consistent with prior studies reporting widespread contamination linked to collection methods and storage containers (18). Even though samples in this study were collected directly from open air, coliform and E. coli contamination exceeded permissible levels, underscoring the need for further investigation into contributing factors and the development of improved rainwater harvesting systems that reduce microbial contamination.

The findings demonstrate that rainwater quality in Thailand frequently fails to meet physical and bacteriological standards, while chemical contaminants were generally within safe limits. Regional differences reflect a combination of geographical, environmental, and pollution-related factors. To ensure the safe use of rainwater for consumption, region-specific water treatment strategies should be developed. Moreover, future research should expand sample sizes and focus on agricultural areas to better evaluate contamination risks and environmental determinants. Such evidence will be critical for informing public health policy, guiding community practices in rainwater use, and promoting sustainable water resource management.

Conclusion

The assessment of the rainwater quality from 152 samples across various regions in Thailand reveals that no samples met all evaluation criteria completely. At least one parameter, either physical or biological, failed to meet the standards in each sample. The notable exception was a sample from the Northeast region, where a toxic heavy metal, mercury, was detected at one station.

The study's findings underscore the importance of continuous monitoring and stringent quality control measures to ensure safe drinking water. The detection of chemical contaminants, although in small quantities, highlights the ongoing risk posed by agricultural and industrial activities. Regulatory agencies must enforce stricter controls on pesticide and herbicide use and promote sustainable agricultural practices to mitigate these risks.

The physical quality parameters, particularly apparent color and pH, require targeted interventions. Regions with high apparent color values and pH deviations should be prioritized for remedial actions, such as implementing filtration systems and addressing contamination sources. Public awareness campaigns are also crucial for educating communities on the importance of maintaining water quality.

Recommendations

The categorization of water quality parameters into color-coded groups provides an effective communication tool for conveying water quality status to the public and policymakers. This approach can help prioritize monitoring efforts and allocate resources to regions and parameters requiring immediate attention.

Therefore, the study highlights the need for a comprehensive and integrated approach to water quality management in Thailand. By addressing the identified areas of concern and implementing effective monitoring and regulatory measures, Thailand can ensure the provision of safe and high-quality potable water, contributing to public health and environmental sustainability. Continuous efforts in monitoring, regulation, and public awareness are essential to achieving this goal

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