Green Technologies and Sustainability 4 (2026) 100444

Contents lists available at ScienceDirect

Green Technologies and Sustainability

journal homepage: https://www.keaipublishing.com/en/journals/green-technologies-and-sustainability/

Full-length article

Developing a policy roadmap for emerging contaminants in drinking water of Thailand

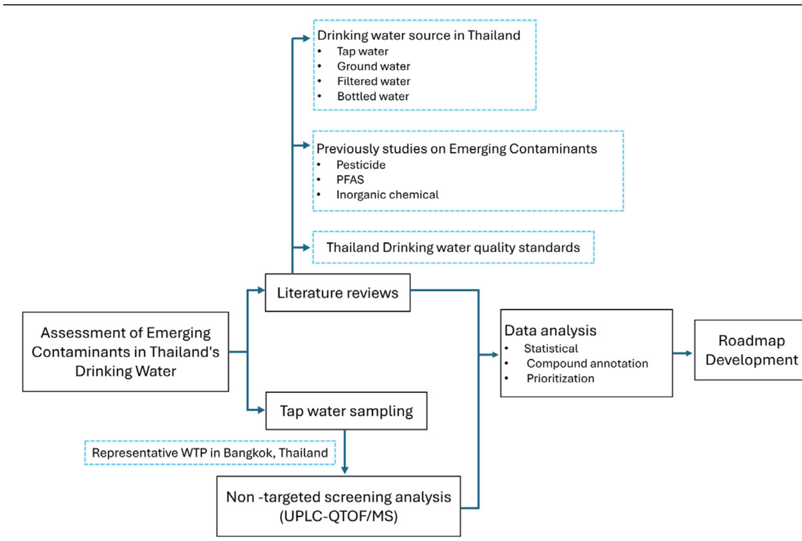
Sarima Niampradit [a,b], Wissanupong Kliengchuay [a,b], Tret C. Burdette [c], Kunrunya Sutan [d], Yanin Limpananont [a,b], Suwalee Worakhunpiset [a,b], Surat Hongsibsong [e,d], Duangrat Inthorn [f], Ahmad Zaharin Aris [g,h], Kyungho Choi [i], Parinya Panuwet [j,k,*], Kraichat Tantrakarnapa [a,b,**]

[a] Department of Social and Environmental Medicine, Faculty of Tropical Medicine, Mahidol University, Bangkok 10400, Thailand
[b] Environment, Health & Social Impact Unit, Faculty of Tropical Medicine, Mahidol University, Bangkok 10400, Thailand
[c] Center for Applied Isotope Studies, University of Georgia, Athens, GA 30602, United States
[d] Research Institute for Health Sciences, Chiang Mai University, Chiang Mai 50200, Thailand
[e] School of Health Sciences Research, Research Institute for Health Sciences, Chiang Mai University, Chiang Mai 50200, Thailand
[f] Faculty of Environment and Resource Studies, Mahidol University, Nakhon Pathom 73170, Thailand
[g] International Institute of Aquaculture and Aquatic Sciences, Universiti Putra Malaysia, 71050 Port Dickson, Negeri Sembilan, Malaysia
[h] Department of Environmental Science and Technology, Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[i] Graduate School of Public Health, Seoul National University, Gwanak-gu, Seoul 08826, South Korea
[j] Division of Environmental Laboratory Sciences, Department of Environmental Protection, Lawrence, MA, 01843, United States
[k] Gangarosa Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, GA, 30328, United States

HIGHLIGHTS

- Scoping review confirms widespread pesticide and PFAS contamination in Thai water.
- Non-targeted screening identifies hundreds of unregulated pharmaceuticals in tap water.
- Current Thai regulations lack oversight for many detected emerging contaminants.
- A five-phase ten-year roadmap provides a framework for national policy reform.
- Study offers a replicable water safety model for other Southeast Asian nations.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Drinking water

ABSTRACT

Safe access to drinking water is critical for community health outcomes; however, Thailand remains challenged by the ongoing chemical contamination of its water resources. This mixed methods study aims to develop

* Corresponding author.
** Corresponding author at: Department of Social and Environmental Medicine, Faculty of Tropical Medicine, Mahidol University, Bangkok 10400, Thailand.
E-mail addresses: parinya.panuwet@emory.edu, parinya.panuwet@mass.gov (P. Panuwet), kraichat.tan@mahidol.ac.th (K. Tantrakarnapa).

https://doi.org/10.1016/j.grets.2026.100444
Received 20 February 2026; Received in revised form 12 June 2026; Accepted 23 June 2026
Available online 26 June 2026

Chemical contaminant
Water quality
Non-target screening analysis
Policy roadmap

a strategic roadmap for sustainable drinking water quality control in Thailand. First, a systematic scoping review of peer-reviewed publications was conducted to evaluate the state of chemical contamination in water resources in Thailand. Concurrently, a non-targeted analysis (NTA) of water samples taken from two representative water treatment plants in Bangkok was conducted to generate the primary data to inform the development of the roadmap. The systematic scoping review has revealed the presence of various contaminants across multiple water sources, including pesticides, per- and polyfluoroalkyl substances, metals, and other inorganic chemicals. These contaminants are frequently associated with agricultural runoff, industrial activities, and inadequate waste management. NTA further annotated hundreds of suspected compounds, with pharmaceuticals and pesticides being the most prominent classes, many of which are not currently regulated in Thailand. Although Thailand's national regulations usually match the international standards, there are still considerable gaps in the total number of regulated chemicals, enforcement strategies, and monitoring of emerging contaminants. The proposed roadmap addresses these gaps in five integrated phases: comprehensive assessment, regulatory enhancement, infrastructure upgrades, capacity building, and long-term sustainability measures. It also emphasizes the needs for public engagement and improved waste management to improve the drinking water quality. This study lays the groundwork for evidence-based policy reform and underscores the need for a unified framework to ensure the safety of drinking water in Thailand.

1. Introduction

Globally, access to safe and clean drinking water is fundamental to public health and sanitation. However, the world is facing a growing water crisis, driven by population growth, pollution, and increasing freshwater consumption. Driven by socio-economic development and shifting consumption patterns, a nearly 1% annual increase in freshwater demand is projected to cause water scarcity for a significant portion of the global population. Forecasts indicate a potential impact on 22%–34% of people worldwide by 2050 [1,2]. Drinking water contaminants originate from industrial effluents, agricultural runoff, wastewater discharge, and improper waste disposal. These pollutants are transported through surface water, soil infiltration, and groundwater flow into drinking water treatment systems. Many persist after incomplete removal and eventually reach humans through tap water consumption and household use. Consequently, humans are the primary receptors at risk of chronic health effects [3]. This crisis is exacerbated by the increasing release of chemical contaminants into the environment, posing a direct risk to human health [4]. Although chemical contamination of drinking water often receives less attention than microbial contamination, it typically presents long-term, serious health risks. Unlike microbial contaminants, which usually cause immediate illness, the adverse effects of chemical contaminants often manifest over extended periods. This delayed manifestation makes them a significant threat to public health [5]. These chemical contaminants in drinking water have been linked to a wide range of adverse health outcomes, including cancer, cardiovascular disease, neurological disorders, and miscarriage [6]. They can be naturally occurring or anthropogenic, and originate from sources such as industrial activities, agricultural practices, and mining operations [7]. Chemical contaminants include heavy metals, pesticides, plasticizers, bacterial toxins, and human or animal drugs [8,9].

In Southeast Asia, rapid urbanization combined with threats from agricultural and manufacturing activities, excessive chemical use, and inadequate wastewater treatment poses significant challenges in maintaining raw water quality [10]. The persistence of multiple chemical pollutants in the environment can lead to contamination of both surface water and groundwater, which are the primary sources for drinking water production. Removing these pollutants, even at low concentrations, presents a considerable challenge for drinking water production [11]. In Thailand, the annual domestic water consumption reaches 3895 million cubic meters. This water was sourced from surface water (64%) and groundwater (36%). The majority of this water, 3403 million cubic meters (87%), is supplied as tap water by over 238 water treatment plants operating nationwide. The remaining 13% comes from surface water and groundwater sources developed for individual household use [12]. Most water treatment plants in Thailand use conventional treatment systems. Only a few utilize advanced technologies such as reverse osmosis (RO), primarily in island areas reliant on seawater desalination, and Dissolved Air Flotation (DAF), used for surface water sources with light sediment loads (such as algae) and turbidity below 100 NTU [13]. Despite these challenges, Thailand demonstrates relatively good access to water, with per capita domestic consumption at 160 liters per day. According to the World Health Organization (WHO) criteria, this falls within the "Optimal Access" range, indicating a low level of health concern related to water scarcity [14]. However, despite achieving 99.5% access to clean drinking water, maintaining its quality remains a challenge in Thailand. Data from the Ministry of Public Health's report on drinking water quality from 2009–2019 revealed that only 40.8% of water available to households was suitable for consumption without further treatment. A significant proportion (43.7%) required additional treatment before consumption, whereas 15.5% was contaminated with chemicals exceeding recommended limits [15]. This status highlights the urgent need to improve water management and treatment strategies to ensure safe and high-quality drinking water for the population [15].

The present study aims to address these pressing issues through three interconnected objectives: (1) to establish a baseline by summarizing the presence and potential sources of chemical contamination in various drinking water supplies in Thailand through a systematic scoping review; (2) to address critical data gaps by characterizing current and emerging contaminants (including chemicals not frequently/routinely monitored) in Bangkok's tap water using non-targeted analysis (NTA); and (3) to synthesize these findings into a comprehensive roadmap for enhanced drinking water quality control and management in Thailand. The use of NTA approach enables the comprehensive detection of both current and emerging contaminants that conventional targeted analyses may overlook, providing a more holistic understanding of water quality risks. This study is the first to employ NTA to assess chemical contaminants in Thailand's drinking water, combined with a systematic scoping review of existing water quality standards and the current contamination status. The findings provide new insights into contaminant occurrence and offer a transferable framework and roadmap for improving drinking water safety in other developing regions facing similar challenges.

2. Method

2.1. Research framework

The research framework for this study outlines the development of a water quality control roadmap for Thailand through an integrated mixed-methods approach consisting of a systemic scoping review and a laboratory analysis using an NTA approach. For the systematic scoping review, the primary review question guiding the initial phase was: "What is the nature and extent of peer-reviewed evidence on chemical contaminants in drinking water in Thailand?" This systematic scoping review was conducted to establish a comprehensive baseline of known contaminants and regulatory gaps.

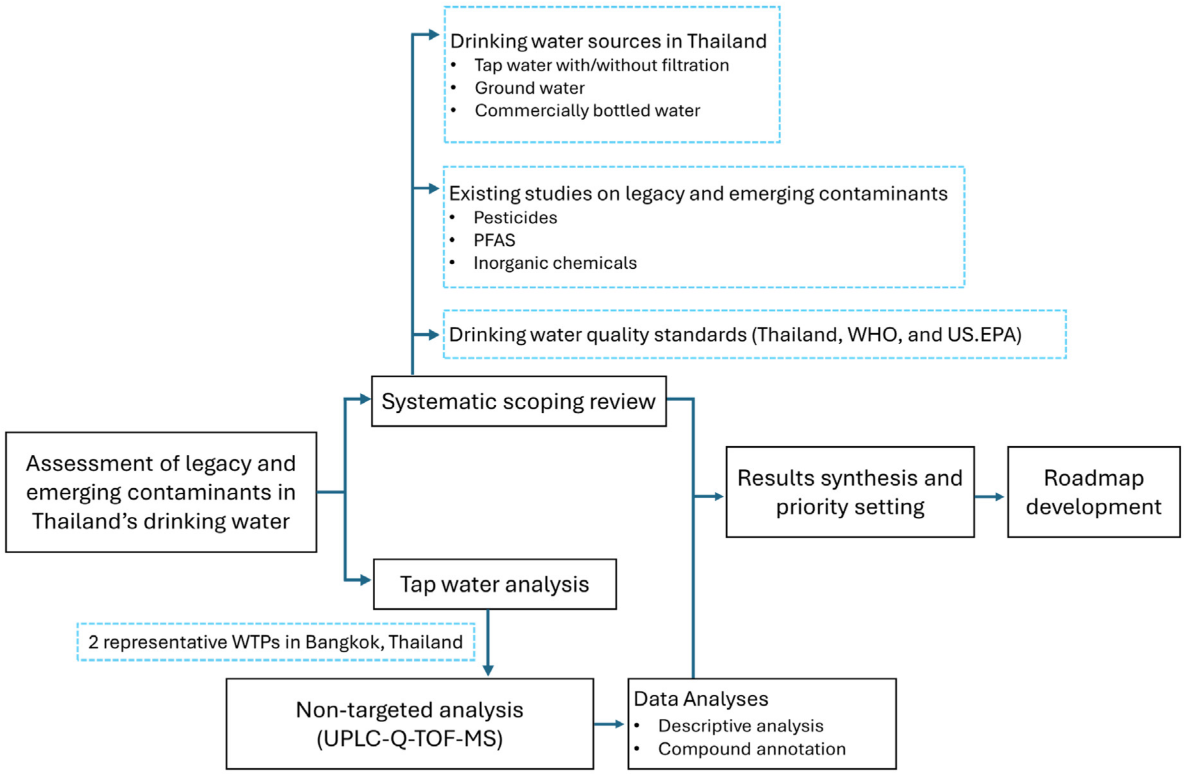


Fig. 1. Research framework for legacy and emerging contaminants in Thailand's drinking water.

We also asked another research question: "Does the current evidence gathered from peer-reviewed publications represent the true extent/magnitude of drinking water contamination from emerging chemicals or any contaminants not frequently monitored?" and proceeded to collecting additional, primary data. These primary data were generated through NTA of tap water samples collected from two water treatment plants (WTPs) in Bangkok using ultra-high-performance liquid chromatography quadrupole time-of-flight mass spectrometer (UPLC-Q-TOF-MS). Following this, the NTA data were analyzed to identify current/legacy chemicals and annotate emerging contaminants. Finally, the baseline evidence from the scoping review and the suspected contaminant profiles generated from the NTA were integrated through a process of results synthesis and priority setting. This process was undertaken to identify and rank priority policy and management actions based on the collective findings, thereby informing the development of a comprehensive roadmap for strengthening drinking water quality control in Thailand. The structural flow and integration of these components are conceptualized in Fig. 1.

2.2. Systematic scoping review

2.2.1. Search strategy

A systematic scoping review was conducted to investigate the current state of chemical contamination in drinking water in Thailand. The design and execution of this systematic scoping review were guided by the combined methodological frameworks of Arksey and O'Malley and Levac et al. [16,17]. The reporting of the review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines [18] and managed using the Covidence software. The completed PRISMA-ScR checklist is provided in Table S1 of the supplementary data. A comprehensive search of Scopus, PubMed, and Google Scholar was conducted, with the final database search completed in November 2025. To ensure transparency and reproducibility, the following full electronic search string was applied across all databases: ("drinking water" OR "tap water" OR "groundwater") AND ("contaminant" OR "chemical" OR "pollutant" OR "emerging pollutants" OR "emerging contaminant" OR "heavy metal" OR "PFAS" OR "Pesticide" OR "plasticizers" OR "pharmaceuticals" OR "EDCs" OR "Endocrine disrupting compounds") AND ("Thailand")

2.2.2. Inclusion and exclusion criteria

Inclusion criteria were limited to only peer-reviewed, English-language, articles on chemical pollutants in drinking water sources such as tap water, bottled water, filtered water, and groundwater published from 2003–2023. Peer-review status was used strictly as an eligibility criterion for publication type, while the assessment of study quality and risk of bias was conducted independently during data extraction. Non-peer-reviewed articles, conference abstracts, and gray literature (such as government or institutional reports) were excluded from the quantitative synthesis matrix to maintain analytical consistency. However, these documents were utilized qualitatively to inform the regulatory baseline and policy roadmap development (Section 3.3).

2.2.3. Data abstraction and bias analysis

Data abstraction was performed using a standardized form to extract key information, including study year, location, water source, contaminant type, analytical method, and concentration range [19]. Study quality and potential bias were assessed based on clarity of objectives, sampling design, analytical reliability, and completeness of reporting, following international guidance from WHO [20]. Studies with insufficient methodological detail or unclear results were interpreted cautiously during synthesis.

2.2.4. Review of drinking water quality standards in Thailand

Data on Thailand's drinking water quality standards was obtained through a document review of official publications from the Ministry of Public Health, the Office of National Water Resources, and the Ministry of Natural Resources and Environment. Key documents, including the Criteria for Recommendation of Drinking Water Quality Surveillance and related regulations, were examined. These materials were compared with international guidelines from the WHO and US EPA to identify consistencies and regulatory gaps.

2.2.5. Data visualization

Spatial data visualization was performed to illustrate the geographic distribution of reported drinking water contaminants in Thailand. Figures were generated using compiled review data, and the base map was obtained from MapChart (https://www.mapchart.net).

2.3. Non-targeted analysis

2.3.1. Chemical and materials

Both parent and isotopically labeled standards (IS) of bisphenol A (and the D6 isotope), triclosan (and the D3 isotope), atrazine (and the D5 isotope), and sulfamethoxazole benzene (and the D4 isotope) were purchased from Dr. Ehrenstorfer (Augsburg, Germany). These reference standards were used for Level I Confirmation. Both LC-MS and HPLC-grade solvents were obtained from Merck (New Jersey, USA), and ultrapure water (18.2 MΩ cm resistivity at 25 °C) was generated using a Millipore (Massachusetts, USA) purification system. Samples were extracted using Strata-X 33 μm polymeric reversed-phase solid-phase extraction cartridges (500 mg/6 mL) from Phenomenex (California, USA). Prior to the analysis, the Extracts were further filtered through 0.2 μm polytetrafluoroethylene (PTFE) syringe filters from VertiPure™.

2.3.2. Sample collection, preparation, and analysis

Tap water samples were collected from two water treatment plants (WTPs) that serve as primary supply hubs for the Bangkok Metropolitan Region, which houses over 11 million residents and accounts for approximately 17% of the total Thai population. These sites, denoted as WTP A and WTP B, were strategically selected to represent the two distinct raw water sources for the capital: the Chao Phraya River and the Mae Klong River, respectively.

The Chao Phraya River basin, supplying WTP A, flows through 11 major provinces in the central plains, serving as a vital hydrological lifeline for over 9.3 million residents (14.3% of the national population) and supporting intensive agricultural runoff across 13,000 km^2 alongside heavy industrial zones. Many WTPs in the central plains draw water from The Chao Phraya River to produce tap water. Similarly, the Mae Klong River basin, supplying WTP B via a 106-kilometer canal, spans 30,200 km^2 across 8 provinces in western Thailand. This basin services over 2.1 million residents (3.4% of the national population) and experiences major anthropogenic pressures from 8000 km^2 of agricultural land, commercial livestock farming, and regional food and sugar industries [21]. Consequently, the raw water entering both facilities carries a complex mixture of contaminants that closely mirrors the primary pollution challenges faced by major river basins nationwide.

Both WTP A and WTP B employ conventional surface water treatment systems commonly used by municipal WTPs in Thailand. The treatment configurations include chemical coagulation, sedimentation, filtration, and disinfection prior to distribution [22]. WTP B additionally incorporates treatment steps such as activated carbon and supplementary chemical treatment, which may contribute to the differences in contaminant removal performance between the two systems. A cross-sectional sampling approach was employed, focusing on finished water quality. Two-liter water samples were collected in September 2023 from specific sampling taps at each WTP. These exact locations correspond to the internal quality control points used by the WTP laboratories to verify water safety standards prior to distribution to consumers, and these sampling points are explicitly marked in Fig. 2.

Samples were collected in pre-cleaned glass bottles and transported to the laboratory in an ice chest maintained at 4 °C. Upon arrival, the samples were filtered through 0.2 μm glass microfiber filters (47 mm) and refrigerated at 4 °C. Extraction was performed within 48 h of collection to ensure sample integrity. Sample preparation and extraction followed a modified protocol based on USEPA Method 1694 and Wee et al. [23,24]. Solid-phase extraction (SPE) was conducted using Phenomenex Strata-X 33 μm polymeric reversed-phase cartridges (500 mg/6 mL), with detailed procedures provided in supplementary information (section S1). Chemical analysis was performed using an Agilent 6546 series ultra-high-performance liquid chromatography quadrupole time-of-flight mass spectrometer (UPLC-QTOF/MS) in both positive and negative ionization modes (Agilent, USA). An Agilent Poroshell 120 EC-C18 column (2.1 × 150 mm, 1.9 μm) was used for positive ionization mode, while a Phenomenex Kinetex EVO C18 100 Åanalytical column (150 × 2.10 mm, 5 μm) was used for negative ionization mode. The optimized UPLC-QTOF/MS instrument parameters are summarized in Table S2.

2.3.3. Quality assurance and quality control

To ensure data integrity, method blanks were prepared using deionized water and extracted alongside samples to monitor background contamination. IS from Dr. Ehrenstorfer (Augsburg, Germany) were used as internal standards: bisphenol A (propane-D6) and triclosan D3 (2,4-dichlorophenoxy D3) for negative ionization mode, and Atrazine D5 (ethylamino D5) and sulfamethoxazole benzene D4 for positive ionization mode. IS recoveries ranged from 92.04% to 124.79%, indicating acceptable method performance. Real-time mass calibration was performed by continuous infusion of reference masses (positive: 121.0509 and 922.0098; negative: 68.9957, 112.9855, and 301.9981) to maintain mass axis accuracy. This calibration ensured highly reliable measurements for tentative contaminant screening and validation in all samples. IS were monitored for all sample injections to ensure instrument m/z error ranges were within acceptable levels.

2.3.4. Compound identification, annotation, and data analysis

The screening analysis is presented in Figure S1. First, the raw LCMS data files were converted to .mzML format using ProteoWizard's msConvert software [25]. Chemical annotation was performed using R Studio (version 4.4.1) with the 'xMSannotator' [26], 'Spectra', and 'plyr' packages. The software was used to annotate detected features (m/z) in the LCMS runs using the Toxin and Toxin Target Database (T3DB) [27,28]. A maximum of 10 ppm error was allowed and retention times for peaks had to be within 15 s to be considered for peaks across samples. Correlations were determined using Pearson correlations and all steps of the multilevel annotation were performed, with checks for redundancies [26]. The analysis focused on M+H and M-H adducts for positive and negative ionization, respectively. Medium confidence and higher results were taken for consideration. This approach allowed for level 4 identification by assigning high confidence formulas to the peaks found in multiple samples that fit the criteria described by Schymanski et al. [29]. For statistical mapping, the 95% confidence intervals of retention times were calculated. The isotope results falling within these intervals were then averaged to represent each provisional annotation. Noted that the availability of the reference standards for bisphenol A, triclosan, atrazine, and sulfamethoxazole allows for identification of these compounds with level I confidence.

2.4. Result synthesis and roadmap generation

The synthesis process integrated data from the systematic scoping review and NTA to identify key contaminants, exposure pathways, and management gaps. Quantitative data were summarized using descriptive statistics and compared against national and international drinking water standards [30,31]. Qualitative data were analyzed thematically to demonstrate emerging contaminant trends and identify policy gaps. A structured framework was then applied to translate the findings into a practical roadmap for water quality management. The roadmap development followed a multi-criteria decision-making approach adapted from the OECD and WHO guidelines, which emphasizes risk prioritization, evidence-based standard setting, and adaptive management [31,32]. Key phases included data integration, expert consultation, and framework validation to ensure scientific rigor and policy relevance.

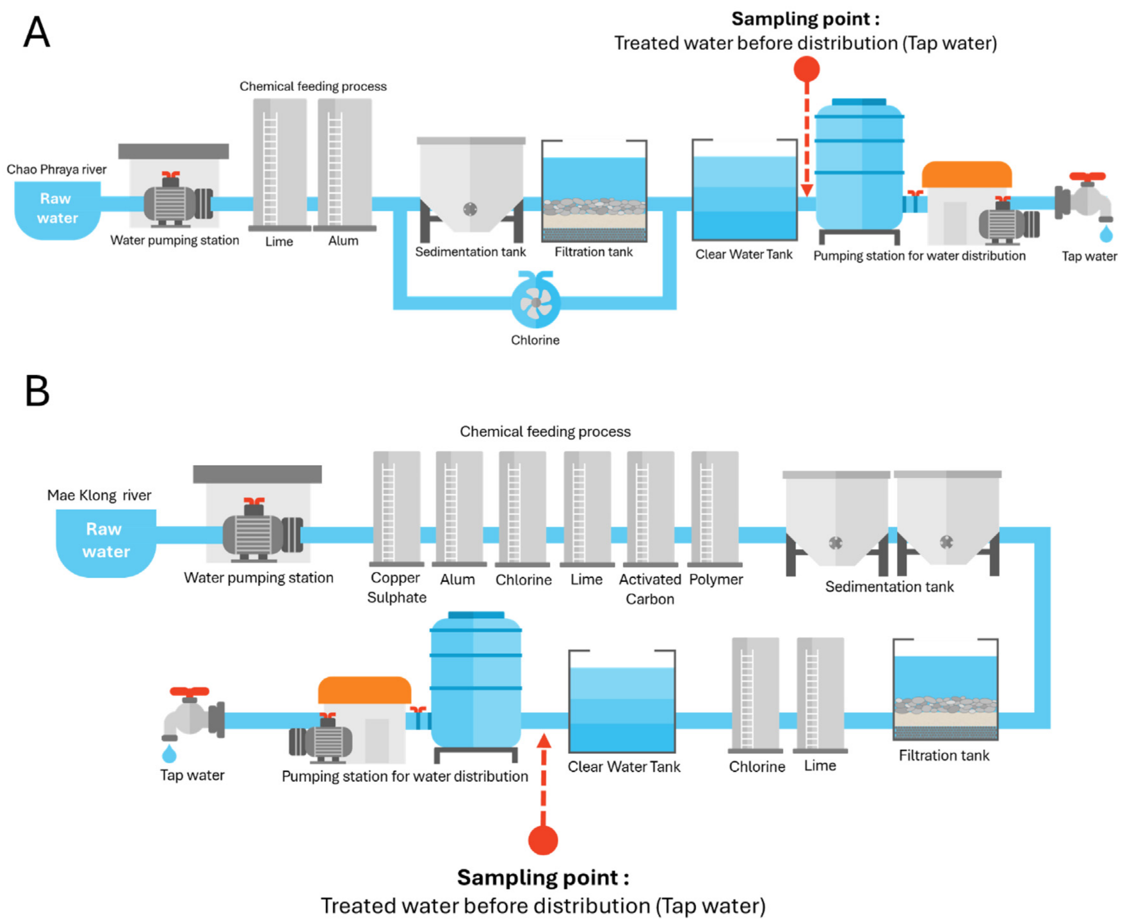


Fig. 2. Schematic diagram of water treatment processes and designated sampling points at (A) WTP A and (B) WTP B.

3. Result and discussion

3.1. Current status of drinking water contamination in Thailand

The PRISMA diagram in Figure S2 shows that 613 studies were initially identified. After removing 121 duplicates and screening abstracts, 439 studies were excluded. A full-text review of the remaining papers resulted in 30 studies meeting the inclusion criteria.

According to the systematic scoping review, the most commonly reported classes of contaminants in Thailand's drinking water include pesticides, PFAS, and inorganic chemicals (Tables S3–S6). These contaminant groups were selected for detailed analysis based on their frequency of occurrence, environmental persistence, and potential health impacts. Monitoring data across Thailand revealed that contamination is not confined to specific regions but occurs across diverse hydrological and land-use settings, reflecting both agricultural and industrial influences. The geographic distribution of these monitored provinces is illustrated in Fig. 3.

This widespread detection of environmental contaminants aligns with the low levels of public confidence in domestic tap water quality. Despite continuous government efforts to maintain municipal safety standards, a contrast persists between actual water infrastructure and public perception. A national survey conducted by the Health Impact Assessment Division, [33], approximately 54% of respondents were not sure if tap water was safe to drink, while 17% firmly believed it was not drinkable, and only 27% believed it was safe to drink (Fig. 4). This skepticism is reflected in drinking water consumption patterns, with sealed small volume bottled water serving as the primary drinking source at 54.1%, followed by domestic filtered tap water and 20-liter commercially bottled water, which are utilized equally at 19.4% each [33]. This data source indicates that Thai people do not trust the quality of tap water, underscoring the critical need for improving public trust by implementing stricter chemical controls described in the 10-year management roadmap developed in this study.

3.1.1. Pesticides

Pesticide contamination in Thailand's drinking water is summarized in Table S3. As an agriculturally intensive country, Thailand continues to increase its import of hazardous agricultural chemicals [34]. Multiple studies have documented the presence of pesticides in drinking water, particularly in farming communities. Klaimala et al. reported common detections of fenitrothion, profenofos, fenthion, atrazine, and aminomethylphosphonic acid (AMPA) in household drinking water from Nakornsawan, Phitsanulok, and Yasothorn provinces [35]. Jaipieam et al. found higher concentrations of organophosphate pesticides in groundwater used for household purposes in agricultural communities compared to non-agricultural areas [36]. In southern Thailand, pesticide residues such as DDE, lindane, alachlor, and 2,4-DDD were found in groundwater samples near vegetable, rubber, and fruit cultivation zones [37]. Similarly, Thapinta and Hudak detected several banned pesticides, including dieldrin, aldrin, heptachlor, and heptachlor epoxide, in groundwater wells across Kanchanaburi, Ratchaburi, and Suphan Buri provinces, indicating long-term persistence [38]. Contamination is not limited to rural areas; atrazine was detected in tap water from the Bang Khen WTPs in Bangkok at levels similar to those found in the source water, suggesting ineffective removal by conventional coagulation and filtration processes [11].

Pesticide residues detected in Thai drinking water systems are comparable to findings reported across other agricultural regions in Asia (Table S7), though concentrations vary by crop type and treatment

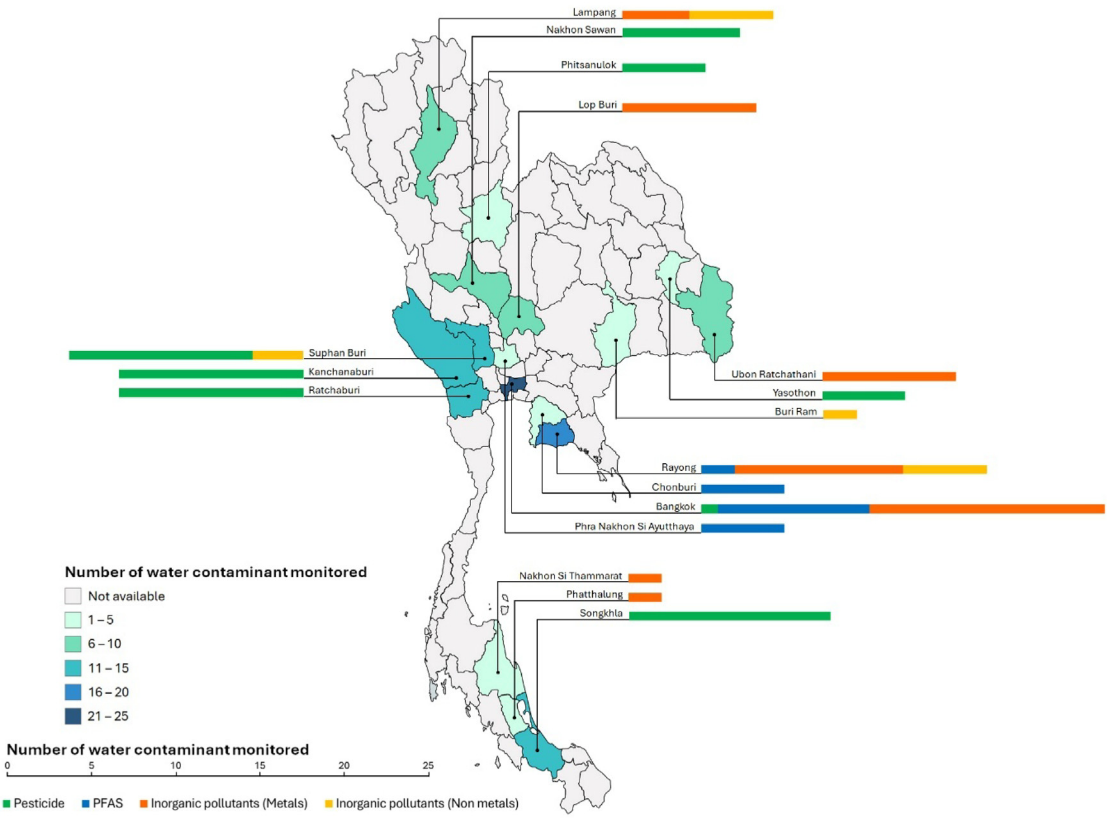


Fig. 3. Provinces where drinking water contamination has been monitored.

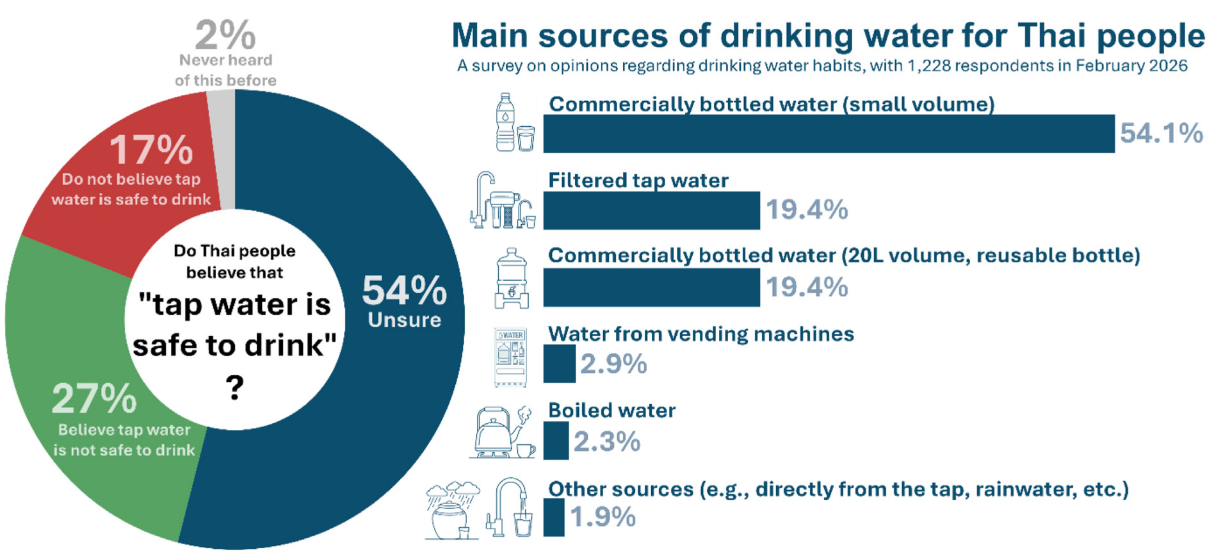


Fig. 4. Integrated survey metrics detailing domestic drinking water sources and public perception regarding tap water potability in Thailand. Data source: Bureau of Food and Water Sanitation, and Health Impact Assessment Division [33].

efficiency. In Vietnam, triazines and chlorpyrifos were dominant in Hanoi tap water, reaching median concentrations of 39.3 ng/L [39], while in Japan, rice-field herbicides such as bentazone and bromobutide reached up to 4.6 μg/L in treated water [40]. In northern India, difenoconazole and chlorpyrifos were detected up to 0.82 μg/L, posing potential human health risks [41]. In China, pyrethroid insecticides were found in tap water with mean concentrations of 0.56 ng/L, indicating relatively lower contamination levels [42]. Meanwhile, in South Korea, metolachlor and alachlor were the most frequently detected in agricultural groundwater, though concentrations averaged only 0.0008 μg/L, suggesting limited infiltration into deeper aquifers [43]. Compared with other countries, Thailand shows a similar pesticide profile, mainly organophosphates and triazines, with higher concentrations in intensive farming areas.

3.1.2. Per- and polyfluoroalkyl substances (PFAS)

Table S4 summarizes the occurrence of PFAS in drinking water in Thailand. Currently, Thailand's drinking water standards do not include specific limits for PFAS, despite their persistence in the environment and potential health risks. Lertassavakorn et al. reported

PFOS concentrations in tap water near the Map Ta Phut Industrial Estate reaching 54.2 ng/L, exceeding the US EPA guideline, reflecting both source water contamination and inadequate treatment [44]. In contrast, bottled water from the same area showed much lower PFAS levels, suggesting greater removal efficiency through advanced treatment. However, Kunacheva et al. found PFAS levels in bottled water in Bangkok ranging from 0.22 to 10.55 ng/L, which in some cases exceeded levels in local tap water, indicating variability in treatment effectiveness [45]. Similarly, Tabtong et al. found that conventional treatment systems in Bangkok could not effectively remove PFAS, while advanced methods such as granular activated carbon and reverse osmosis achieved over 86 percent removal [46]. PFAS concentrations in Bangkok tap water ranged between 0.58 and 1.15 ng/L, and household filtration was found to further reduce contamination [46]. Regarding groundwater, Hongkachok et al. observed higher PFAS levels near industrial waste disposal sites in Ayutthaya and Chonburi, suggesting industrial activities as a significant contamination source [47].

Compared to other Asian countries (Table S8), PFAS concentrations in Thai drinking water are within a similar range but still indicate localized contamination risks in industrial areas. In Malaysia, total PFAS concentrations in tap water ranged from 0.08 to 171.3 ng/L, dominated by PFBA and PFOA, with higher levels observed in urbanized regions such as Hulu Langat and Sepang [48]. In China, PFAS levels reached up to 365 ng/L in tap water and 97 ng/L in bottled water, with PFBA, PFHxA, and PFHxS being the predominant compounds [49,50]. Similarly, in South Korea, the median Σ PFAS concentration in tap water was 11.9 ng/L, mainly composed of PFHxS and PFOA [51], while Singapore reported much lower concentrations, ranging from 0.30 to 15.17 ng/L, due to advanced treatment and strict source control [52]. Across Asia, short-chain PFAS such as PFBA, PFHxA, and PFBS have become increasingly dominant, reflecting the shift from long-chain PFASs following international phase-outs of PFOS and PFOA. Overall, the findings indicate that PFAS contamination in Thailand, while moderate compared to regional levels.

3.1.3. Inorganic chemicals

Inorganic chemical contamination in Thailand's drinking water is presented in Table S5 (metals) and Table S6 (non-metals), with findings varying across water sources. Most bottled and filtered water samples fell within standard limits, although some studies reported exceedances of arsenic and lead. For instance, 17.6% of bottled water brands in Bangkok contained arsenic above the Thai and international limit of 10 μg/L [53], while lead exceedances were observed in 8.34% and 9.09% of samples from Nakhon Si Thammarat and Phatthalung provinces, respectively [54,55]. Filtered water generally complied with standards, though lead levels exceeded limits in 6.06% of samples from a child development center in Phatthalung [55], highlighting the need for cost-effective household filtration solutions [56]. Groundwater studies in Bangkok, Rayong, Kalasin, Lopburi, and other provinces show overall compliance, but certain regions have elevated concentrations of sodium, uranium, and heavy metals. Notably, arsenic concentrations in Rayong groundwater reached up to 183 μg/L, alongside excessive levels of cadmium, lead, manganese, and selenium, largely attributed to industrial and agricultural activity [11,57–59]. Non-metal inorganic pollutants were also detected in groundwater across multiple provinces, with some samples showing high levels of chloride, sulfate, nitrate, and fluoride, potentially reflecting fertilizer use, saline intrusion, or geological conditions [59–63]. Tap water samples in Bangkok and the metropolitan area generally met regulatory standards [11], though elevated heavy metal levels were reported at the point of use, possibly due to leaching from old plumbing systems [53]. Localized contamination was found in areas such as Sri Chang Island, where seawater-based supplies contained high sodium and boron concentrations [11], and in southern provinces, where 18.19% of school tap water samples in Nakhon Si Thammarat and 12.12% in Phatthalung exceeded lead and cadmium limits [54,55].

Compared with other Asian countries (Table S9), the occurrence of inorganic contaminants in Thailand's drinking water is consistent with patterns reported across the region. In Malaysia, Azrina et al. found low concentrations of metals in tap water, with only minor exceedances of iron and manganese [64]. In Myanmar, Maw et al. observed arsenic, lead, iron, and manganese above WHO limits in several townships, mainly from industrial and natural sources [65]. In China, Zhou et al. reported elevated iron, manganese, and copper in tap water linked to higher health risks, although most concentrations were within standards [66]. In Japan, Ohno et al. showed that heavy metals contributed less than ten percent of total daily intake due to effective treatment systems [67]. In contrast, Korea showed severe groundwater contamination, where arsenic, lead, and nitrate frequently exceeded WHO limits, reflecting impacts from urban and industrial activities [68]. Overall, Thailand's inorganic contamination levels are moderate compared to neighboring countries, but localized exceedances of arsenic, manganese, and lead in groundwater near industrial areas indicate the need for improved monitoring and corrosion control in water systems.

3.2. Detection of suspected emerging chemicals in Tap water in Thailand

This study analyzed tap water from two WTPs supplying Bangkok and metropolitan areas, which utilize distinct water sources (Fig. 2). NTA detected 19,701 and 58,434 chromatographic features in tap water samples from WTP A and WTP B, respectively. After data alignment and quality filtering, 1638 features in WTP A and 3483 in WTP B were annotated through database matching (mass error ≤10 ppm). Following isotopic and retention time validation, 299 and 400 compounds were putatively identified with level IV confidence [26], representing provisional annotations that require subsequent target confirmation. Bisphenol A, triclosan, atrazine, and sulfamethoxazole benzene were identified with level I confidence. Among these compounds, only atrazine was confirmed in finished tap water samples.

Tap water produced from the Chao Phraya River source (WTP A) showed a higher chemical contaminant load than that from the Mae Klong River source (WTP B). This difference potentially reflects both variations in source water characteristics and treatment practices. The Chao Phraya River, the longest river in Thailand at approximately 372 km, flows through densely populated and industrialized provinces before reaching the Gulf of Thailand. Along its course, it receives cumulative pollution from tributaries draining agricultural and urbanized catchments, leading to contaminant accumulation in downstream sections [69]. In contrast, the Mae Klong River originates in Kanchanaburi Province where surrounding land use is mainly forest and agriculture with low industrial activity, resulting in cleaner raw water [70]. Differences in treatment configurations, as illustrated in Fig. 2, and in the types and dosages of treatment chemicals further contribute to variations in water quality between the two systems [11]. Suspected compounds were classified into several use-based categories including pharmaceuticals, pesticides, natural toxins, industrial chemicals, plasticizers, personal care products, research chemicals, derivative compounds, and polycyclic aromatic hydrocarbons (PAHs), as summarized in Fig. 5.

In WTP A, pharmaceuticals accounted for the largest proportion of suspect features (145 features, 36%), followed by pesticides (94, 24%), natural toxins (60, 15%), and industrial chemicals (43, 11%). WTP B showed a similar pattern with pharmaceuticals (101, 34%), pesticides (66, 22%), natural toxins (49, 16%), and industrial chemicals (41, 14%). These patterns suggest broad environmental inputs from urban, agricultural, and industrial activities. Particular attention is warranted for the pharmaceutical class, especially high environmental risk subclasses such as antineoplastic agents [71]. Five antineoplastic substances, methotrexate, mitomycin, mitoxantrone, sorafenib, and trimetrexate, were among the chemicals tentatively annotated in WTP A. Because these compounds were profiled via NTA without reference

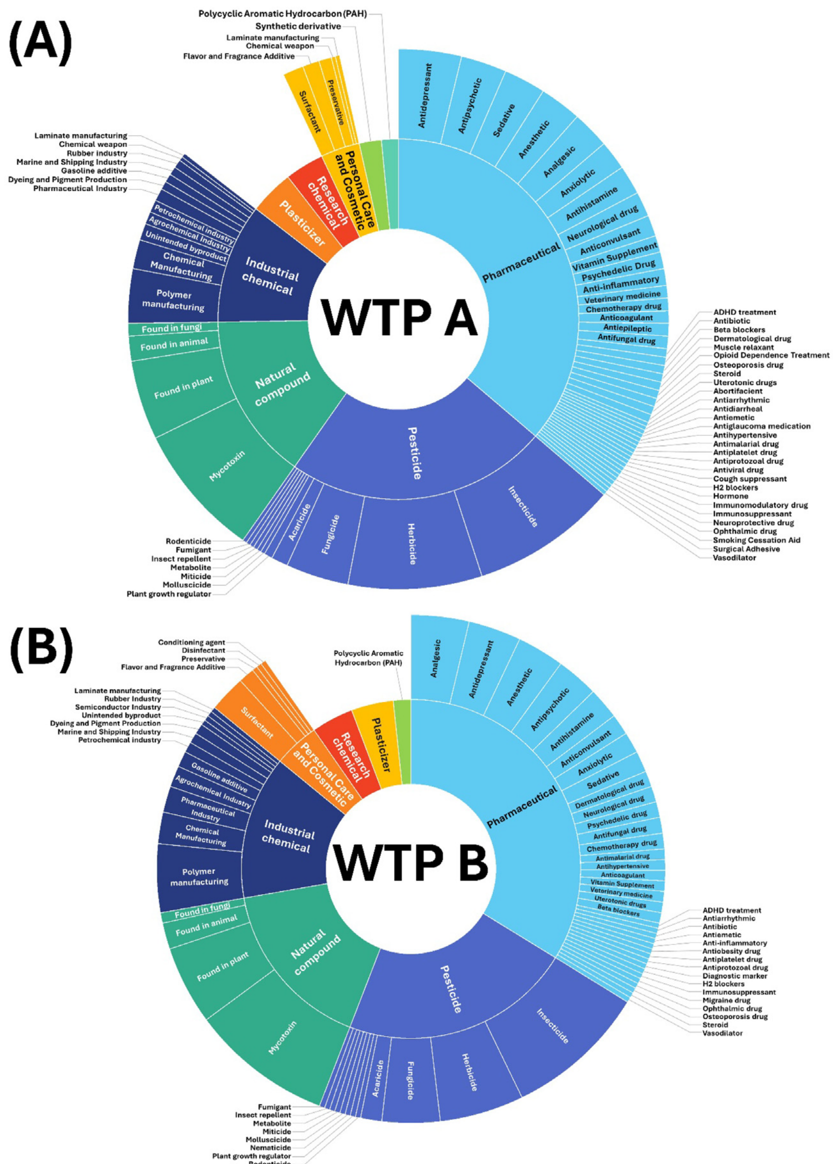


Fig. 5. Chemical analysis of tap water from (A) WTP A and (B) WTP B, showing compounds classified by use.

standards, their presence remains strictly provisional and unconfirmed. While their provisional annotation highlights the potential risk posed by pharmaceuticals in the drinking water supply, confirmatory targeted analyses (or authentication with reference standards) are required before drawing firm conclusions about their definitive presence and exact concentrations. Research on these compounds in Thai drinking water is limited, with most existing studies focusing on surface water or raw water sources [11,72,73]. For example, [73] reported concentrations of 14 pharmaceuticals in Bangkok surface water ranging from <1 to 22,300 ng/L, suggesting potential adverse effects on aquatic organisms. [73]. Consequently, a significant research gap exists regarding the occurrence and fate of pharmaceuticals specifically within the treated drinking water supply.

Several pesticide-related compounds currently listed in the Department of Agriculture of Thailand [74] were also suspected in tap water samples. These include carbofuran, formetanate, methomyl, and carbosulfan, all of which were annotated with provisional confidence at WTP A. Carbofuran is of particular concern due to its high toxicity (oral LDLD_{50} = 8 mg/kg) and resistance to removal by standard water treatment methods [75]. Despite being regulated in Thailand (limit = 0.007 mg/L), it is already banned in many countries (or regions) including the US, EU, and Canada [76]. Additional pesticides tentatively annotated in WTP A include 2,4-Dichlorophenoxyacetic acid (2,4-D) and pendimethalin, both of which are listed in Thailand's drinking water quality standards. Atrazine and butachlor, two of the top ten most imported pesticides in Thailand in 2023 [34], were detected and tentatively annotated, respectively, in tap water from both WTPs, suggesting their significant usage within the country. Chlorpyrifos-methyl, banned in Thailand since 2020 [74], was also among the suspected compounds. Its putative identification may suggest continued illegal use, given its reported aqueous hydrolysis half-life of up to 27 days. However, without absolute retention time and fragments verification via analytical standards, this signal remains tentative. Although the annotation of chlorpyrifos-methyl requires confirmation using authentic standards, the potential occurrence of banned pesticides in drinking water sources raises important concerns regarding the effectiveness of existing regulatory enforcement and surveillance systems. If substances that have already been prohibited continue to enter aquatic environments, this may indicate challenges in compliance monitoring, enforcement, or source control. Such challenges could further complicate efforts to identify, monitor, and manage emerging contaminants that are not yet routinely regulated. The greater number and diversity of suspect features observed in WTP A is likely due to the longer and more heavily urbanized Chao Phraya River catchment (approximately 372 km), which receives input from multiple land use types, including agriculture, industry, and residential areas. In contrast, WTP B sources water from the Mae Klong River, a shorter (approximately 132 km) and more agriculturally dominated system [11,77].

Overall, the NTA results suggest the potential presence of complex mixtures of current and emerging contaminants in treated tap water. However, it is important to note that, without reference standards, NTA provides putative evidence only and does not confirm compound presence or concentration [78]. These findings highlight the need for targeted confirmatory analysis using authentic standards, along with risk-based monitoring frameworks that account for unregulated contaminants [79]. Strengthening source-to-tap management and investing in analytical capacity will be critical for addressing chemical safety in Thailand's drinking water systems.

3.3. A roadmap for improved drinking water quality

3.3.1. Current status of drinking water standards in Thailand

Water resource management is a national priority in Thailand, and the government has pursued an integrated implementation of Sustainable Development Goal 6 (SDG 6) through four main strategies: (1) developing the Master Plan on Water Resources Management (2018–2037) as the national roadmap for sustainable water use; (2) establishing the Office of National Water Resources (ONWR) as the central coordinating body among relevant agencies; (3) enacting the Water Resources Act (2018) as the key legislative framework governing water management; and (4) promoting technology, knowledge, and innovation to strengthen national capacity in water resources management [15,30]. Although no dedicated act exists specifically for drinking water standards, the Ministry of Public Health, through the Department of Health, has issued comprehensive guidelines such as the Standard Criteria for Quality of Drinkable Tap Water 2020 and the Criteria for Recommendation of Drinking Water Quality Surveillance 2020, which encompass multiple sources including tap water, surface water, groundwater, and rainwater [80,81]. Tables 1 and 2 outline the parametric values, which are largely aligned with international standards like WHO and US.EPA [31,82], though coverage of organic compounds remains limited. For example, paraquat, once Thailand's second most imported pesticide, has a standard based on Canadian guidelines. Although it was banned in 2020, data from the Ramathibodi Poison Center reported 124 occupational exposure cases between 2018 and 2021, with no significant difference in case numbers across those years, suggesting continued use and limited enforcement [83,84].

Thailand's water supply is managed by the Metropolitan Waterworks Authority for Bangkok and its vicinity, and 234 regional WTPs for the rest of the country, each following their own quality control measures [85,86]. Additional standards apply to groundwater "Groundwater Quality Standards 2000" and bottled water "Drinking Water in Sealed Containers 2001" [87,88]. Despite this regulatory framework, the Department of Health reported that 65.6% of household water samples in 2022 failed to meet standards, with 11% showing elevated chemical contaminants even after household treatment [89].

Nevertheless, Thailand's drinking water management continues to face major challenges, including fragmented oversight, outdated standards, and limited monitoring of emerging contaminants such as PFAS, pesticides, and inorganic chemicals [46,90]. Current regulations cover only a small fraction of the chemicals detected in recent studies, and conventional treatment systems often fail to remove them effectively [11,46]. This study helps bridge these gaps by consolidating nationwide evidence of chemical contamination across multiple water sources. Frequent detections include banned pesticides [35,38], PFAS near industrial zones [44], and heavy metals in both urban and rural supplies [54,59]. Moreover, our non-target screening analysis revealed hundreds of suspected compounds in treated tap water, notably pharmaceuticals, pesticides, and industrial chemicals, many of which are not regulated under current Thai standards.

While this study expands the chemical evidence base, further work is needed to confirm suspected compounds, assess human health risks, and develop cost-effective treatment technologies. Future research should also examine the relationships between land use, contaminant occurrence, and exposure in vulnerable populations to inform targeted risk management strategies and regulatory reform.

3.3.2. Framework for managing chemical contaminants in drinking water

Ensuring access to safe drinking water in Thailand requires a science-based and adaptive regulatory framework for chemical contaminant management. Given the evolving nature of water pollution from industrial activity, agriculture, and urbanization, both known and emerging contaminants must be addressed systematically.

The proposed dual-pathway framework (Fig. 6) differentiates between contaminants already listed in national standards and those not yet regulated. For listed contaminants, if the concentration remains within acceptable limits, routine monitoring must be conducted to ensure continued compliance. If limits are exceeded, immediate intervention is triggered. Recommended actions include improving water sources, upgrading treatment processes using technologies such as activated carbon filtration, reverse osmosis, or advanced oxidation processes, and enhancing regulatory enforcement [95,96]. At the same time, a scientific review of the contaminant's occurrence, health effects, and environmental relevance should be carried out to inform regulatory actions.

For unlisted contaminants, the framework begins with evidence gathering through systematic scoping reviews, NTA, and expert consultation. The systematic scoping review provides information on the occurrence, distribution, and existing evidence of contaminants reported in Thailand, while the NTA identifies previously unmonitored or emerging contaminants that may not be captured by routine monitoring programs. Together, these complementary sources of evidence support the identification of contaminants that warrant further investigation and regulatory consideration. This is followed by a structured risk assessment phase that evaluates toxicological data, establishes dose–response relationships, and defines acceptable exposure thresholds (US.EPA, 2025). The standard-setting process proposes guideline limits based on health and ecological safety, while considering international benchmarks and local conditions. This phase also involves stakeholder consultation and formal integration with regulatory bodies. The final stage for both listed and newly regulated contaminants involves implementation and monitoring, which includes enforcement, routine water quality assessments, and periodic regulatory review.

The framework emphasizes transparency, inter-agency coordination, and periodic review to ensure continual improvement. It provides the foundation for risk-based decision-making and adaptive regulation of chemical contaminants in Thailand's drinking water. To operationalize this structure, a 10-year roadmap was developed to guide phased implementation and long-term water quality improvement (Fig. 6).

3.3.3. Roadmap for drinking water quality control in Thailand

The 10-year roadmap for drinking water quality improvement in Thailand was developed based on evidence from this study and international guidelines from the OECD and WHO, ensuring that it is both scientifically grounded and policy-relevant [31,32]. Based on data from major urban supply systems, this roadmap is designed as a flexible and adaptable framework rather than a rigid national mandate, allowing for local adjustments due to specific regional contamination profiles and infrastructure capacities.

The roadmap outlines a phased approach to strengthen regulatory systems (Fig. 7), enhance infrastructure, and improve institutional capacity for water safety management across the country. Phase 1 focuses on baseline assessment through nationwide surveys, hotspot mapping,

Table 1
Standard limits for inorganic contaminants in drinking water.

Inorganic chemicals	MCL (mg/L)	Guideline value (mg/L)	Thailand's Drinking Water Standard (mg/L)					
	US EPA[a]	WHO[b]	Drinking water[c]	MWA Tap water[d]	PWA Tap water[e]	Drinkable Tap water[f]	Ground water[g]	Bottled water[h]
Toxic chemical								
Aluminium	–	–	0.2	0.2	–	–	–	0.2
Antimony	0.006	0.02		0.02	–	–	–	–
Arsenic	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.05
Barium	2	1.3	0.7	1.3	0.7	–		1
Beryllium	0.004	–	0.004	–	–	–	–	–
Boron	–	2.4	2.4	–	–	–	–	–
Cadmium	0.005	0.003	0.003	0.003	0.003	0.003	0.003	0.005
Chromium	0.1	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Copper	1.3	2	1	1	2	1	1	1
Cyanide	0.2	–	0.07	0.07	0.07	–	0.2	0.1
Lead	0.015	0.01	0.01	0.01	0.01	0.01	0.01	0.05
Manganese	–	0.08	0.3	0.08	0.1	0.3	0.5	0.05
Mercury	0.002	0.006	0.001	0.006	0.001	0.001	0.001	0.002
Nickel	–	0.07	0.07	0.07	–	–	0.02	–
Silver	–	–	–	0.1	–	–	–	0.05
Selenium	0.05	0.04	0.01	0.04	0.01	–	0.01	0.01
Thallium	0.002	–	–	–	–	–	–	–
Uranium	–	0.03	–	–	–	–	–	–
Non-toxic chemical								
Chloride	–	–	250	250	250	250	600	250
Fluoride	4	1.5	0.7	0.7	1.5	0.7	1	1.5
Hardness ($CaCO_3$)	–	–	300	300	300	300	500	100
Iron	–	–	0.3	0.3	0.3	0.3	–	0.3
Nitrate (as N)	10	–	–	–	–	–	–	4
Nitrite (as N)	1	–	–	–	–	–	–	–
Nitrate (as NO_3)	–	50	50	50	50	50	45	–
Nitrite (as NO_2)	–	3	3	3	3	3	–	–
Sulfate	–	–	250	250	250	250	250	250
TDS	–	–	500	1000	1000	500	1200	500
Zinc	–	–	3	3	3	3	5	5

[a] National Primary Drinking Water Regulations by United States Environmental Protection Agency [82].
[b] Guidelines for Drinking-water Quality by World Health Organization [91].
[c] Notification of the Department of Health on Criteria for Recommendation of Drinking Water Quality Surveillance [80].
[d] The Metropolitan Waterworks Authority (MWA) of Thailand's Tap Water Quality Standards [85].
[e] The Provincial Waterworks Authority (PWA) of Thailand's Tap Water Quality Standards [86].
[f] Notification of the Department of Health on Criteria for the Quality of Drinkable Tap Water [81].
[g] Ministry of Industry Announcement No. 12 (1999) Issued under the Groundwater Act, 1977, Regarding the Establishment of Technical Regulations and Measures for the Prevention of Public Health Hazards and Environmental Pollution. [92].
[h] Ministry of Public Health Announcement No. 61 (1981) on Drinking Water in Sealed Containers [93].

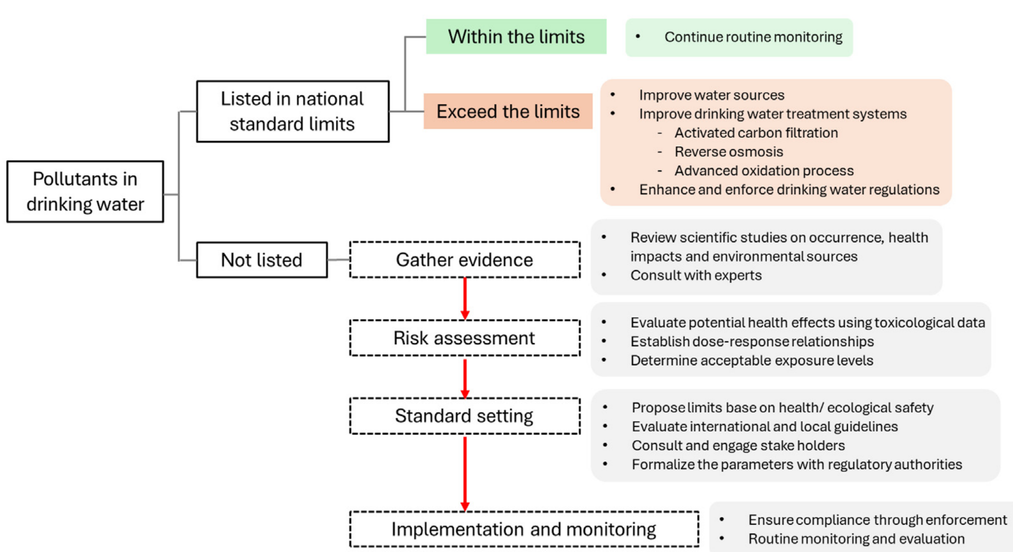


Fig. 6. Framework for managing chemical contaminants in drinking water.

Table 2
Standard limits for organic contaminants in drinking water.

Organic chemicals	MCL (mg/L)	Guideline value (mg/L)	Thailand's Drinking Water Standard (mg/L)			
	US EPA[a]	WHO[b]	Drinking water[c]	MWA Tap water[d]	PWA Tap water[e]	Ground water[f]
Acrylamide	0.05% dosed at 1 mg/L	0.0005	–	–	–	–
Alachlor	0.002	0.02	–	–	–	–
Aldicarb	–	0.01	–	–	–	–
Aldrin and dieldrin	–	0.00003	–	–	0.00003	0.00003
Atrazine	0.003	0.1	0.002	0.002	–	0.003
Benzene	0.005	0.01	0.01	0.01	–	0.005
Benzo(a)pyrene (PAHs)	0.0002	0.0007	–	–	–	0.0002
Bromodichloromethane	–	0.06	0.06	0.06	0.06	–
Bromoform	–	0.1	0.1	0.1	0.1	–
Carbofuran	0.04	0.007	0.007	0.007	–	–
Carbon tetrachloride	0.005	0.004	0.004	0.004	–	0.005
Chlordane	0.002	0.0002	–	–	0.0002	0.0002
Chlorobenzene	0.1	–	–	–	–	–
Chloroform	–	0.3	0.3	0.3	0.3	–
Chlorotoluron	–	0.03	–	–	–	–
Chlorpyrifos	–	0.03	0.03	0.03	–	–
Cyanazine	–	0.0006	–	–	–	–
2,4-Dichlorophenoxyacetic acid (2,4-D)	0.07	0.03	–	0.03	–	0.03
2,4-DB	–	0.09	–	–	–	–
DDT	–	0.001	0.001	0.001	0.001	0.002
Dalapon	0.2	–	–	–	–	
Dibromoacetonitrile	–	0.07	–	–	–	–
Dibromochloromethane	–	0.1	0.1	0.1	0.1	
1,2-Dibromo-3-chloropropane (DBCP)	0.0002	0.001	–	–	–	–
1,2-Dibromoethane	–	0.0004	–	–	–	–
Dichloroacetate	–	0.05	–	–	–	–
Dichloroacetonitrile	–	0.02	–	–	–	–
o-Dichlorobenzene	0.6	1	–	–	–	–
p-Dichlorobenzene	0.075	0.3	–	–	–	–
1,2-Dichloroethane	0.005	0.03	0.03	0.03	–	0.005
1,1-Dichloroethylene	0.007	–	–	–	–	0.007
cis-1,2-Dichloroethylene	0.07	0.05	–	–	–	0.07
trans-1,2-Dichloroethylene	0.1	0.05	–	–	–	0.1
Dichloromethane	0.005	0.02	0.02	–	–	0.005
1,2-Dichloropropane	0.005	0.04	–	–	–	–
1,3-Dichloropropene		0.02	–	–	–	–
Dichlorprop	–	0.1	–	–	–	–
Di(2-ethylhexyl) adipate	0.4	–	–	–	–	–
Di(2-ethylhexyl) phthalate	0.006	0.008	–	–	–	–
Dimethoate	–	0.006	–	–	–	–
Dinoseb	0.007	–	–	–	–	–
1,4-Dioxane	–	0.05	–	–	–	–
Dioxin (2,3,7,8-TCDD)	0.00000003	–	–	–	–	–
Diquat	0.02	–	–	–	–	–
Edetic acid	–	0.6	–	–	–	–
Endothall	0.1	–	–	–	–	–
Endrin	0.002	0.0006	–	–	–	–
Epichlorohydrin	0.01% dosed at 20 mg/L	0.0004	–	–	–	–
Ethylbenzene	0.7	0.3	0.3	0.3		0.7
Ethylene dibromide	0.00005	–	–	–	–	–
Fenoprop	–	0.009	–	–	–	–
Glyphosate	0.7	–	0.9	0.9	–	–
Heptachlor	0.0004	–	–	–	0.00003	0.0004
Heptachlor epoxide	0.0002	–	–	–	0.00003	0.0002
Hexachlorobenzene	0.001	–	–	–	0.001	
Hexachlorobutadiene	–	0.0006	–	–	–	–
Hexachlorocyclopentadiene	0.05	–	–	–	–	–
Hydroxyatrazine	–	0.2	–	–	–	–
Isoproturon	–	0.009	–	–	–	–
Lindane	0.0002	0.002	–	–	0.002	0.0002
Mecoprop	–	0.01	–	–	–	–
Methoxychlor	0.04	0.02	–	–	0.02	–
Metolachlor	–	0.01	–	–	–	–
Microcystins	–	0.001	–	0.001	–	–
Molinate	–	0.006	–	–	–	–
Monochloroacetate	–	0.02	–	–	–	–
N-Nitrosodimethylamine (NDMA)	–	0.0001	–	–	–	–
Oxamyl (Vydate)	0.2	–	–	–	–	–
Paraquat	–	–	0.01	0.01		
Polychlorinated biphenyls (PCBs)	0.0005	–	–	–	–	0.0005
Pendimethalin	–	0.02	–	–	–	–

(*continued on next page*)

Table 2 (*continued*).

Organic chemicals	MCL (mg/L)	Guideline value (mg/L)	Thailand's Drinking Water Standard (mg/L)			
	US EPA[a]	WHO[b]	Drinking water[c]	MWA Tap water[d]	PWA Tap water[e]	Ground water[f]
Pentachlorophenol	0.001	0.009	–			0.001
Picloram	0.5	–	–	–	–	–
Saxitoxins	–	0.003	–	–	–	–
Simazine	0.004	0.002	–	–	–	–
Styrene	0.1	0.02	0.02	0.02		0.1
2,4,5-T	–	0.009	–	–	–	–
Tetrachloroethene	–	–	0.04	0.1	–	–
Tetrachloroethylene	0.005	0.1	–	–	–	0.005
Terbuthylazine	–	0.007	–	–	–	–
Toluene	1	0.7	0.7	0.7		1
Toxaphene	0.003	–	–	–	–	–
2,4,5-TP (Silvex)	0.05	–	–	–	–	–
Trichloroacetate	–	0.2	–	–	–	–
1,2,4-Trichlorobenzene	0.07	–	–	–	–	–
Trichloroethene	–	0.008	0.07	0.008	–	–
1,1,1-Trichloroethane	0.2	–	2	2		0.2
1,1,2-Trichloroethane	0.005	–	–	–	–	0.005
Trichloroethylene	0.005	–	–	–	–	0.005
2,4,6-Trichlorophenol	–	0.2	–	–	–	–
Trifluralin	–	0.02	–	–	–	–
Vinyl chloride	0.002	0.0003	0.0003	–	–	0.002
Xylenes	10	0.5	0.5	–	–	10

[a] National Primary Drinking Water Regulations by United States Environmental Protection Agency [82].

[b] Guidelines for drinking-water quality by World Health Organization [91].

[c] Notification of the Department of Health on Criteria for Recommendation of Drinking Water Quality Surveillance [81].

[d] The Metropolitan Waterworks Authority (MWA) of Thailand's Tap Water Quality Standards [85].

[e] The Provincial Waterworks Authority (PWA) of Thailand's Tap Water Quality Standards [86].

[f] Announcement of the National Environment Board No. 20 (2000) Issued under the Enhancement and Conservation of National Environmental Quality Act, B.E. 2535 (1992) Regarding the Establishment of Groundwater Quality Standards [94].

and health impact studies to provide essential data that will inform future interventions. The outcomes from this phase are expected to reduce uncertainty around contaminant distribution and create a foundation for evidence-based decision-making. In Phase 2, this information is leveraged to strengthen standards and enforcement mechanisms by aligning national regulations with international benchmarks, particularly targeting contaminants identified during the initial assessment. Rather than serving as a generic best practice, Phase 2 is directly anchored to the critical gaps identified in our review and NTA. Specifically, it targets the immediate formal standard-setting for unmonitored substances like PFAS, while concurrently reinforcing enforcement protocols to address the illegal or continued use of prohibited chemicals, such as chlorpyrifos-methyl. This regulatory coherence will reduce confusion among stakeholders and enable more effective monitoring and compliance. Phase 3 involves infrastructure upgrades, including improvements to water treatment plants, distribution networks, and the integration of real-time monitoring systems. These developments are anticipated to significantly improve the quality and reliability of drinking water, especially in rural and underserved areas. Importantly, infrastructure improvements in this phase should be tailored to the specific needs of each region, such as addressing saline intrusion in coastal areas or agricultural runoff in northern provinces. Phase 4 emphasizes capacity building and public engagement, promoting local ownership of water management through training programs, awareness campaigns, and citizen science initiatives. This phase not only empowers communities but also ensures that technological investments are sustainably operated and maintained. Finally, Phase 5 focuses on long-term sustainability by establishing mechanisms for integrated water resource management, continuous performance evaluation, and periodic review of drinking water policies and regulations. These activities help ensure that improvements achieved in earlier phases are maintained and adapted to future challenges.

This roadmap provides a scientifically grounded and forward-looking strategy to strengthen Thailand's drinking water safety and governance, promoting a transition from fragmented and reactive management toward a more coordinated, resilient, and sustainable system. By emphasizing adaptability and regional relevance, the framework can serve as a model for other developing countries facing similar environmental and regulatory challenges, while ensuring that water safety interventions are effective across diverse local contexts.

To ensure the feasibility of this 10-year roadmap, implementation is structured into short-term (Phases 1–2: Years 1–3), medium-term (Phases 3–4: Years 4–7), and long-term (Phase 5: Years 8–10) horizons. Operationalizing this framework requires dedicated human capacity, including environmental toxicologists, water treatment engineers, and specialized analytical technicians. Key stakeholders must assume distinct roles: regulatory bodies (e.g., the Ministry of Public Health and the Office of National Water Resources) will oversee standard-setting and enforcement, while local water authorities manage infrastructure upgrades. Furthermore, public engagement will be driven through community-based water monitoring apps and targeted educational campaigns, fostering behavioral adaptation and local ownership of water resources.

3.4. Strengths and limitations

This study provides a comprehensive assessment of chemical contamination in Thailand's drinking water, integrating evidence from a nationwide systematic scoping review, comparison with international regulatory benchmarks, and advanced NTA application. A key strength lies in the systematically evaluating both regulated and current/emerging contaminants across multiple water sources, leading to the identification of critical management gaps and offering evidence-based recommendations for policy reform and monitoring improvement. The inclusion of global benchmarks (WHO and US EPA) strengthens the relevance and comparability of the findings, while the NTA application provides novel insight into the occurrence of previously unrecognized contaminants in treated tap water.

However, several limitations should be acknowledged. First, the systematic scoping review was restricted to English-language, peer-reviewed studies, potentially omitting localized gray literature or unpublished technical data from domestic agencies. This restriction introduces a spatial bias toward regions with high academic research

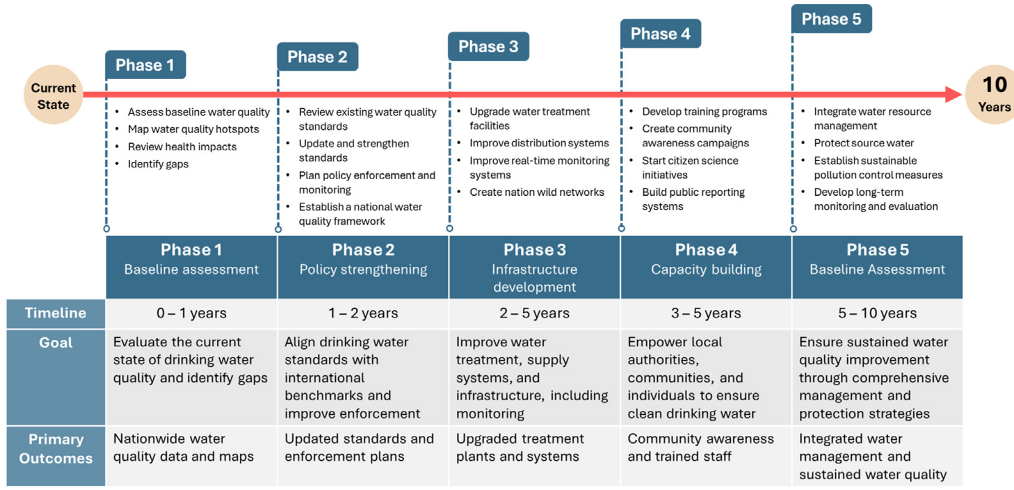


Fig. 7. Roadmap for improving drinking water quality in Thailand.

activity, such as the Bangkok Metropolitan Region, while under-representing routine national monitoring networks. Second, the NTA application was limited to two major WTPs in the Bangkok Metropolitan Region at a single time point. These chemical profiles represent a temporary snapshot that may not fully capture seasonal variations, hydrological fluctuations, or the dynamics of smaller municipal and rural water systems with different contamination sources and infrastructure capacities. Additionally, the majority of NTA results were assigned level IV confidence and therefore provide putative evidence rather than confirmed identifications. Although a small number of compounds were identified with level I confidence using authentic reference standards, most annotations should be considered provisional and could only be used to partially demonstrate contaminant profiles and trends. Consequently, these provisional annotations cannot be directly used for quantitative risk assessment or immediate regulatory mandates without subsequent targeted quantification and validation using authentic reference standards.

Nevertheless, the policy roadmap developed in this study is designed to cover the whole country. The proposed roadmap is not site-specific to the selected urban WTPs. Instead, it offers a comprehensive, scalable framework and practical national strategies, such as expanding parametric monitoring and establishing inter-agency water safety plans, which can be universally adapted and deployed across standard municipal WTPs throughout Thailand to strengthen drinking water safety guidelines. Ultimately, acknowledging these limitations helps position the proposed roadmap as an initial, evidence-informed framework designed to guide future surveillance and adaptive water management. This roadmap, however, serves as a critical first step for advancing Thailand's water quality management and provides a flexible framework for other developing countries facing similar environmental and regulatory settings.

4. Conclusion

This study provides a comprehensive assessment of chemical contamination in Thailand's drinking water and highlights systemic gaps in current water quality management. Although national standards are largely aligned with international benchmarks, they remain limited in scope, particularly for emerging contaminants. The systematic scoping review synthesized data across drinking water sources (tap, bottled, filtered, and groundwater) revealing detections of heavy metals, pesticides, PFAS, and other inorganic chemicals. Many of these contaminants exceed allowable limits or remain unregulated, especially in agricultural and industrial regions, raising concerns about long-term public health risks and environmental impacts. To build on these findings, this study applied NTA to tap water from two major water treatment plants in Bangkok. The results showed hundreds of suspected chemical features, predominantly pharmaceuticals, pesticides, and industrial compounds. These findings suggest an increasing chemical complexity in treated water and underline the limitations of current treatment processes and regulatory coverage. Importantly, the detection of putatively annotated banned pesticides raises critical questions regarding the robustness of the existing enforcement system; if the current infrastructure struggles to restrict already prohibited substances, its capacity to monitor and manage truly emerging contaminants remains heavily compromised. Addressing these challenges requires a strategic and integrated approach. This paper proposed a national framework and roadmap structured in five phases, including baseline assessments, policy updates, infrastructure improvement, capacity building, and long-term sustainability. The roadmap explicitly signals that reinforcing enforcement capacities for existing standards must be executed concurrently with the development of new baseline regulations for unlisted substances. Together, these strategies aim to strengthen contaminant regulation, advance treatment technologies, and promote public engagement. Moving forward, improved surveillance, risk-based prioritization, and interdisciplinary research will be critical to ensuring safe and sustainable drinking water for all communities in Thailand. These findings and the proposed management approaches are directly relevant to neighboring countries, particularly in Southeast Asia (for example, Vietnam, Cambodia, Laos, Myanmar, and Malaysia), where similar agricultural practices, industrial activities, and regulatory challenges exist, and thus this paper can be adapted to inform regional surveillance strategies, risk assessments, and policy development.

CRediT authorship contribution statement

Sarima Niampradit: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Wissanupong Kliengchuay:** Writing – review & editing, Methodology, Conceptualization. **Tret C. Burdette:** Writing – review & editing, Validation, Formal analysis. **Kunrunya Sutan:** Formal analysis, Conceptualization. **Yanin Limpananont:** Writing – review & editing, Conceptualization. **Suwalee Worakhunpiset:** Writing – review & editing, Conceptualization. **Surat Hongsibsong:** Writing – review & editing, Conceptualization. **Duangrat Inthorn:** Writing – review & editing, Funding acquisition, Conceptualization. **Ahmad Zaharin Aris:** Writing – review & editing, Investigation, Conceptualization. **Kyungho Choi:** Writing – review & editing, Investigation, Conceptualization. **Parinya Panuwet:** Writing

– review & editing, Supervision, Methodology, Investigation, Conceptualization. **Kraichat Tantrakarnapa:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Disclaimer

The views expressed in this paper are those of the individual and do not necessarily represent the views of the Massachusetts's Department of Environmental Protection.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research project is supported by Royal Golden Jubilee PhD, National Research Council of Thailand (NRCT): NRCT5-RGJ63012-137, to S.N, we also thank the Department of Social and Environmental Medicine, and Environment, Health & Social Impact Unit, Faculty of Tropical Medicine, Mahidol University, Thailand, Research Institute for Health Sciences, Chiang Mai University and Rollins School of Public Health, Emory University, and The Metropolitan Waterworks Authority for support all and equipment and facility.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.grets.2026.100444.

Data availability

Data will be made available on request.

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