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Assessment of fecal contamination and its potential risks of rainwater collected in Hanoi city, Vietnam

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ABSTRACT

Fecal indicator bacteria (FIB) are used worldwide as indicators of fecal contamination in water, particularly in drinking water. This paper aims to investigate the level of FIB contamination and its associated public health risks in rainwater samples collected at 22 sites in inner-urban and suburban districts of Hanoi City during the period from May 2023 to May 2025. The results showed higher FIB values in inner-urban districts where high population densities were reported. The mean values of TC and EC in raw rainwater at most sites observed were higher than the limits of the Vietnam national technical regulation for domestic water use and also the WHO (2022) guideline for drinking water. A high public health risk was identified, and rainwater was unsuitable for direct potable use without treatment. Thus, our results underscore the importance of preventive and treatment measures to mitigate the risks associated with using harvested rainwater. Both natural and anthropogenic factors are primarily influencing the spread and persistence of FIB in this study. Our results provide a scientific basis for policy-making in air environmental protection for Hanoi City, as well as other large cities in developing countries in Asia.

Keywords: Fecal indicator bacteria, *Escherichia coli*, rainwater, potential risk assessment, urban areas, Hanoi, wet deposition.

1. Introduction

Rainwater, often considered a domestic water source, provides various social, economic, and environmental benefits, particularly in areas prone to flooding, water scarce, or where groundwater and surface water are polluted (Quinn et al., 2021; Nandi & Gonela, 2022). Rainwater is becoming increasingly important as global domestic water demand is projected to rise significantly, up to 300% from 2010 to 2050 (Boretti & Rosa, 2019), coupled with concerns over the safety of existing water sources due to depletion, pollution, and outdated infrastructure (Nandi & Gonela,

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2022). However, rainwater can be strongly contaminated with various chemical pollutants and bacteria (Hamilton et al., 2019; Zdeb et al., 2021; Archundia et al., 2025). Numerous studies demonstrated that rainwater in different regions contains a variety of pathogenic microorganisms (Martin et al., 2010; Nwogu et al., 2024; Anindita et al., 2025). The presence of pathogenic microorganisms in rainwater can lead to various health issues in ecosystems, animals, and humans (Anindita et al., 2025). For example, various bacteria, such as Salmonella, Campylobacter, Legionella, and *Escherichia coli* (*E. coli*), present in rainwater, can cause gastrointestinal illnesses, respiratory issues, and pneumonia in humans (Zdeb et al., 2025; Anindita et al., 2025). The World Health Organization has noted that rainwater may contain an increased prevalence of *E. coli* and other bacteria that cause diarrhea (WHO, 2019).

Fecal indicator bacteria (FIB) are used worldwide as indicators of fecal contamination in surface water (Stocker et al., 2019; Le et al., 2023, 2024) and rainwater (Ewelike et al., 2020; Tenebe et al., 2020; Liu et al., 2025). In recent years, due to the potential impact of rainborne microorganisms on the environment and public health, FIB numbers in rainwater have attracted increasing attention in different regions of the world (Kleinheinz et al., 2009; Hamilton et al., 2019; Liu et al., 2025), including urban and industrial, and rural areas (Nwogu et al., 2024; Anindita et al., 2025). For example, the *E. coli* density and the total number of bacteria at 37°C in rainwater samples in the city of Rzeszów, Poland, ranged from not detected to 50 CFU.100 mL^{-1} and from not detected to 6×10^6 $CFU.100mL^{-1}$, respectively (Zdeb et al., 2021). Similarly, a very high value of total coliform density in rainwater, averaging 2.6×10^6 $CFU.100mL^{-1}$, was reported for rural areas of Southeastern Nigeria (Nwogu et al., 2024). These authors recommend that rainwater cannot be consumed without treatment because it poses a risk to public health (Zdeb et al., 2021; Nwogu et al., 2024; Anindita et al., 2025).

Besides, rainwater acts as a sink for atmospheric pollutants. Analysing rainwater composition and quality helps assess the extent and nature of air pollution, identify pollution sources, and understand the impact of air quality on ecosystems and human health (Zeng & Han, 2020; Ariffin et al., 2023). Indeed, such research may provide a scientific basis for giving protection and management strategies that help improve air quality.

Hanoi, a significant economic and cultural centre of Vietnam, is a densely populated area with an average of 2,585 inhabitants per square kilometre in 2023 (Hanoi-GSO, 2024). Previous studies reported that human activities have significantly impacted the air environment in Hanoi (Lasko et al., 2018; Sakamoto et al., 2018; Makkonen et al., 2023). To date, there have been limited studies on rainwater quality (Lee et al., 2017; Tran et al., 2020). Moreover, microbiological assessments, both quantitative and qualitative, have been relatively rare and underexplored, with limited samples. Indeed, Lee et al. (2017) assessed rainwater quality variables to verify the drinking water source for the Cu Khe village in a suburban area, whereas Tran et al. (2020) analyzed some chemical variables of rainwater collected at Hanoi University of Industry in Hanoi City.

This paper presents the results of an observation on the spatial and seasonal variation of FIB contamination (total coliforms (TC) and *Escherichia coli* (EC) densities) in rainwater samples collected in suburban and inner-urban areas of Hanoi City during the period May 2023 - May 2025. The results provide a dataset of microorganisms in raw rainwater, as well as an assessment of human health risks associated with the use of rainwater, particularly for drinking purposes.

The results also provide a scientific basis for improving air quality protection and management strategies in large cities across Asia.

2. Study site and Methodology

2.1. Study site

Hanoi, the capital of Vietnam, is located in a fairly flat area (5–20 m above sea level), with three-quarters of the city's total area being plains, built up by large river branches.

Potential airborne fecal sources for raw rainwater contamination in urban areas include animal feces, human waste, and contaminated dust and particles carried by the wind (Ahmed et al., 2016; Sorkheh et al., 2022; Perera & Magana-Arachchi, 2022). Hanoi covers an area of 3,360 km² with a total population of 8.587×10^6 people in 2023 (Hanoi-GSO, 2024). There are approximately 30 inner-city and suburban districts, and the population density varied significantly across different inner-city and suburban districts. For example, very high population density (in 10^3 inhabitants.km^{-2}) appears in some inner-urban districts in the centre of Hanoi, such as: Dong Da (38.1), Thanh Xuan (32.3), and Hai Ba Trung (28.8) and in sub-urban areas as well, such as Gia Lam (28.8), where land use is mainly for urban area. In contrast, lower population density was reported for some other suburban areas, such as Thach That and Soc Son (1.2), and Son Tay and Phu Xuyen (1.4), where higher proportions of agricultural land (vegetables, flowers, and rice) and forest land were found (Fig. 1).

Additionally, high concentrations of airborne particles may contribute to bacterial contamination in rainwater in metropolitan cities (Sorkheh et al., 2022; Perera & Magana-Arachchi, 2022). For Hanoi city, particulate matter concentration in the air was very high due to biomass burning (especially agricultural field burning), coal combustion, vehicle traffic, heavy fuel oil combustion, industrial and intensive construction activities, and long-range transported aerosols (ACP, 2021; Makkonen et al., 2023).

Hanoi is located in a tropical region where two seasons are distinct: the rainy (wet) season (May to October) and the dry season (November to April). During the rainy season, rainfall accounted for more than 80% of the total annual rainfall (e.g., 1,420 mm.yr^{-1} in 2023 recorded at Lang meteorological station (Hanoi-GSO, 2024)). The air temperature ranged from 18.2 to 31.5°C, averaging 25.8°C for the entire year. Humidity varied from 59% to 82%, with an average of 74% (Hanoi-GSO, 2024).

2.2. Rainwater sampling

A total of 241 rainwater samples were collected at 13 sites in inner-urban districts and 9 sites in sub-urban areas (Table 1, Fig. S1 in Supplementary file) during the period from May 2023 to May 2025. 13 sites in the inner-urban districts included Ba Dinh, Bac Tu Liem, Cau Giay, Gia Lam, Ha Dong, Hai Ba Trung, Hoan Kiem, Hoang Mai, Long Bien, Nam Tu Liem, Tay Ho, Dong Da, and Thanh Xuan. 9 sites in sub-urban districts are Dong Anh, Dan Phuong, Hoai Duc, Phu Xuyen, Phuc Tho, Quoc Oai, Soc Son, Son Tay, and Thach That (Table 1, Fig. S1). The number of samples at each site is given in Table 1.

At each sampling site, three 2L glass beakers were taken to collect rainwater samples. The beakers were placed at a height of 80 cm above the ground to avoid contamination from the surrounding area. Then, all the rainwater collected from these three beakers on a fixed sampling date at each site was well mixed to obtain a representative site sample. The samples were then placed into glass bottles, which were stored in an icebox before being transported to the laboratory on the same day of sampling.

Table 1. FIB numbers (average; min-max values) in rainwater samples collected in 22 districts of Hanoi city

Site location	No	District name	Site name	Date of sampling	Number of samples	TC CFU.100 mL^{-1}	EC CFU.100 mL^{-1}	Population density, 10^3 inhab.km^{-2}
Inner-urban districts	1	Ba Dinh	BD	5/2023-2/2025	7	5,714 (200-17,500)	257 (ND-1,700)	24.1
	2	Bac Tu Liem	BTL	5/2023-5/2025	25	3,460 (300-18,300)	56 (ND-500)	8.1
	3	Cau Giay	CG	6/2023-2/2025	26	3,128 (ND-13,600)	724 (ND-3,200)	23.9
	4	Dong Da	DD	6/2023-2/2025	20	3,535 (200-19,700)	375 (ND-4,300)	38.1
	5	Hai Ba Trung	HBT	6/2023-9/2024	9	2,733 (100-9,600)	22 (ND-200)	28.8
	6	Hoan Kiem	HK	6/2023-7/2024	6	3,517 (1,900-9,200)	500 (ND-1,400)	26.4
	7	Tay Ho	TH	5/2023-7/2024	6	367 (ND-800)	ND (ND-ND)	6.9
	8	Thanh Xua	TX	5/2023-7/2024	6	400 (100-900)	ND (ND-ND)	32.4
	9	Hoang Mai	HM	6/2023-2/2025	22	5,890 (700-15,900)	381 (ND-5,300)	13.9
	10	Gia Lam	GL	6/2023-7/2024	5	2,560 (1,200-3,900)	1,080 (ND-2,800)	26.9
	11	Ha Dong	HD	5/2023-7/2024	9	3,067 (500-11,600)	22 (ND-100)	9.0
	12	Long Bien	LB	6/2023-7/2024	6	1,450 (ND-5,600)	817 (ND-4,900)	5.8
	13	Nam Tu Liem	NTL	9/2023-1/2024	4	5,050 (1,600-9,700)	425 (ND-1,000)	9.5
Sub-urban districts	14	Dong Anh	DA	5/2023-7/2024	9	1,700 (100-3,700)	11 (ND-100)	22.4
	15	Dan Phuong	DP	5/2023-2/2025	14	3,650 (200-15,800)	436 (ND-3,200)	2.4
	16	Hoai Duc	HDC	5/2023-5/2024	8	5,338 (ND-11,300)	50 (ND-300)	3.4
	17	Phu Xuyen	PX	6/2023-1/2024	4	2,700 (800-6,400)	25 (ND-100)	1.4
	18	Phuc Tho	PT	6/2023-5/2025	16	1,425 (200-5,000)	75 (ND-500)	1.7
	19	Quoc Oai	QO	6/2023-9/2024	11	1,536 (400-5,800)	9 (ND-100)	1.4
	20	Soc Son	SS	6/2023-8/2024	10	2,370 (ND-10,400)	130 (ND-1200)	1.2
	21	Son Tay	ST	6/2023-7/2024	8	1,350 (300-4,200)	25 (ND-200)	1.4
	22	Thach That	TT	6/2023-9/2024	10	2,120 (200-10,600)	190 (ND-900)	1.2
Average (Min-max)						*3,071 (ND-19,700)*	*266 (ND-5,300)*	-
QCVN 01-1:2024/BYT						*<1*	*<1*	-
QCVN 08-2023/BTNMT						-	*<20*	-
WHO, 2022						*0*	*0*	

Note: ND: not detected

QCVN 01-1:2024/BYT: National technical regulation on Domestic Water Quality

QCVN 08-2023/BTNMT: Vietnam National Technical Regulation on Surface Water Quality

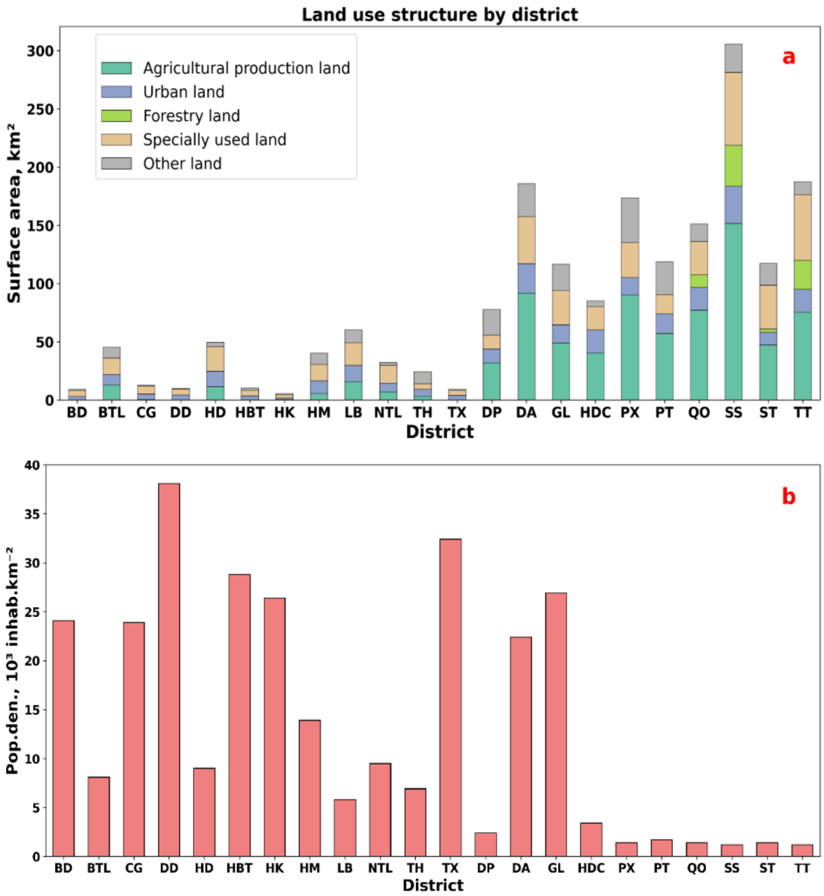

Figure 1. Land use (a) and population density (b) of 22 districts studied in Hanoi city

2.3. Laboratory analysis

The samples were analysed immediately upon arriving at the laboratory. The numbers for TC and EC are determined from unfiltered rainwater samples using a 3M PetrifilmTM *E. coli*/Coliform Count Plate, and the details of the analytical method are given in our previous studies (Le et al., 2023; 2024). Briefly, 1 mL of each sample was inoculated onto a Petri-film EC plate and incubated at 37°C for 24 h (for TC) and then for 48 h (for EC). The number of blue (TC) or red points (EC) was then counted. The final results are expressed in CFU.100 mL^{-1}. When no coliforms are present in the incubated petri-film, the results are noted as not detected (ND).

All glassware was rinsed with deionised water and sterilised before use. Besides, blanks (sterile deionised water) were used to ensure an uncontaminated culture medium for FIB quantification and to ensure no cross-contamination of samples during laboratory processing. Additionally, repeatability of sample analysis was performed in triplicate for each sample. The results here are the mean values of the triplicate analysis.

2.4. Classification of FIB level

Based on EC numbers, WHO (2011) classified drinking water as follows: 0 CFU.100 mL^{-1}: conformity; 1–10 CFU.100 mL^{-1}: low risk; 10–100 CFU.100 mL^{-1}: intermediate risk;

100–1000 CFU.100 mL^{-1}: high risk, and above 1000 CFU.100 mL^{-1}: very high risk.

Besides, based on TC numbers, Amenu & Tafeese (2020) proposed the following water quality classification: 0 CFU.100 mL^{-1}: safe water; 1–10 CFU.100 mL^{-1}: reasonable water; 11–100 CFU.100 mL^{-1}: polluted water; and >100 CFU.100 mL^{-1}: dangerous water. In addition, Niyoyitungiye et al. (2020) determined that potable water can be used if the TC number is lower than 20 CFU. 100 mL^{-1} and no *E. coli* is present. In general, *E. coli* is not typically present in drinking water according to all guidelines.

2.5. Statistical analysis

Pearson correlation coefficients and Principal Component Analysis (PCA) were applied to check the relationship between FIB numbers in rainwater samples and population density or land use in 22 districts. The seasonal and spatial variations of FIB numbers in rainwater samples were examined by using an independent-samples T-test. The statistical analyses were performed using the XLSTAT software (Addinsoft, 2019).

3. Results and discussions

3.1. FIB numbers in rainwater samples in Hanoi city

3.1.1. FIB numbers

TC numbers in rainwater samples collected from 22 districts of Hanoi City from 2023 to 2025 varied in a high range, from undetected (ND) to 19,700 CFU.100 mL^{-1}, with an average of 3,071±3,044 CFU.100 mL^{-1}. The mean values observed at all sites were far higher than the permissible limit specified in the Vietnam technical regulation for domestic water quality QCVN 01-1:2024/BYT (<1 CFU.100 mL^{-1}) and the limit proposed by WHO (2022) (Table 1).

EC numbers in 241 rainwater samples collected across Hanoi city ranged from undetected to 5,300 CFU.100 mL^{-1}, averaging 266±328 CFU.100 mL^{-1}. The mean value of all samples was significantly higher than the permissible value (< 1 CFU.100 mL^{-1}) set by the Vietnamese regulation QCVN 01-1:2024/BYT and also exceeded the allowable value outlined in the WHO's guidelines (WHO, 2022) (Table 1). However, EC was not detected at two sites (TX and TH) (Table 1).

3.1.2. Spatial variation of FIB numbers

Spatially, higher TC values (mean; min-max; in CFU.100 mL^{-1}) were detected at sites of BD (5,714; 200-17,500), HM (5,890; 700-15,900), HDC (5,338; ND-11,300), and NTL (5,050; 1,600-9,700), whereas much lower TC values were found at TH (367; ND-800), TX (400; 100-900), ST (1,350; 300-4,200), and LB (1,450; ND-5,600) (Table 1, Fig. S2a in Supplementary file).

For EC (mean; min-max; in CFU.100 mL^{-1}), higher values were observed at some sites, such as LB (817; ND-4,900), GL (1,080; ND-2,800), CG (724; ND-3,200), and HM (381; ND-5,300). Low EC values were recorded at QO (9; ND-100), DA (11; ND-100), HD (22; ND-100), HBT (22; ND-200), PX (25; ND-100), and ST (25; ND-200). Notably, no EC is present in samples at the TX and TH sites (Table 1, Fig. S2b in Supplementary file).

For both TC and EC, higher values were observed in the inner-urban districts compared to the suburban sites (Fig. 2).

3.1.3. Seasonal variation of FIB numbers

Figure 2 illustrates a slight seasonal variation in both TC and EC values for all observed samples. The mean values of TC and EC (in CFU.100 mL^{-1}) for all samples in the dry season (3,607 and 374, respectively) were higher than those in the rainy season (2,512 and 154, respectively). However, statistical analysis did not show a significant difference ($p > 0.05$).

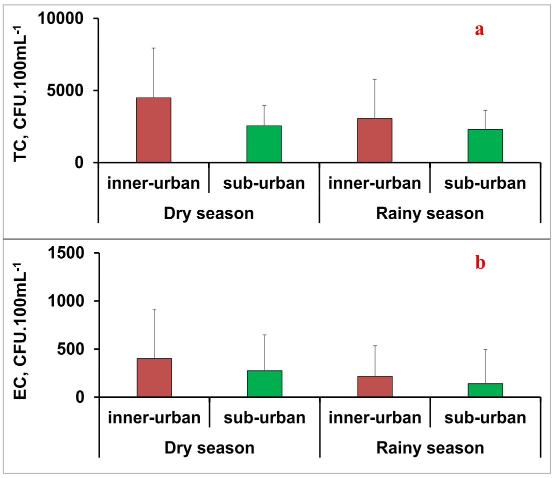

Figure 2. Seasonal variation of TC (a) and EC (b) numbers in rainwater samples in inner-urban and sub-urban areas of Hanoi city during the dry and rainy seasons

3.2. Risk assessment associated with FIB in rainwater collected in Hanoi city

Based on EC numbers observed and the classification method of WHO (2011), the microbial rainwater quality at 11/22 sites was classified at high risk level (100-1000 CFU.100 mL^{-1}); while 8/22 sites were at intermediate risk (10-100 CFU.100 mL^{-1}); and 1/22 sites at low risk (1-10 CFU.100 mL^{-1}) of drinking water without appropriate treatment measures. EC was undetected in the samples at two sites, corresponding with conformity level (0 CFU.100 mL^{-1}) for drinking water.

Based on the TC numbers measured and the classification method proposed by Amenu & Tafeese (2020), all the mean values at 22 sites can be classified as being at a dangerous level for drinking water without appropriate treatment measures.

Our results also revealed that higher values were observed during the dry season and at the beginning of the rainy and wet seasons (notably in samples collected in May). Thus, the health risk of rainwater contaminated with FIB in Hanoi city should be more closely monitored during these periods of the year.

3.3. Comparison with different regions around the world

Many studies have pointed out that harvested rainwater is often strongly contaminated by pathogenic microorganisms worldwide (Olaoye & Olaniyan, 2012; Hamilton et al., 2019; Tenebe et al., 2020; Liu et al., 2025). Table 2 shows the values of FIB numbers in rainwater at different regions of the world for comparison.

FIB numbers in this study were similar to the ones reported by Lee et al. (2017) for Cu Khe village, Hanoi city, where TC numbers (from 10-12,000 CFU.100 mL^{-1}) were present in all rainwater samples, and *E. coli* (from ND-3,200 CFU.100 mL^{-1}), present in 50% of the total samples (Table 2). However, TC and EC numbers in rainwater samples from Hanoi City in this study were higher than those collected in rural or less densely populated areas in Vietnam, such as Vinh Chau town, Soc Trang Province (Nguyen et al., 2019) (Table 2). Nonetheless, our values were lower than some values recorded in other regions in Vietnam or around the World (Table 2). For example, rainwater harvested in the Mekong Delta can have a TC count of up to 102,500 CFU.100 mL^{-1}, which is a significant contamination level primarily attributed to household-specific factors, including rainwater storage, collection, and handling practices (Wilbers et al., 2013). In Southeastern Nigeria, Nwogu et al. (2024) found that the TC numbers in harvested rainwater ranged from undetectable to a very high value of 3.8×10^6 CFU.100 mL^{-1}, averaging 2.6×10^6 CFU.100 mL^{-1} (Table 2). As is known, the use of rainwater contaminated with FIB can pose a significant threat to human and animal health, as well as the aquatic ecosystem, globally (Ahmed et al., 2019; Hamilton et al., 2019; Paruch et al., 2019). In more detail, exposure to FIB-contaminated rainwater, whether through drinking, recreational activities, or even crop irrigation, can lead to gastrointestinal illnesses, skin infections, and other waterborne diseases (Ahmed et al., 2019; Hamilton et al., 2019). Thus, high FIB numbers in rainwater in this study may raise concerns about the safety of using it for potable and non-potable purposes, primarily when proper treatment is not employed.

Table 2. FIB numbers in rainwater in different regions of the world. Values in parallel are the mean or the median

Sites, Country	**Site/sample description**	**Observation date**	**Total coliforms CFU.100 mL^{-1} or MPN.100 mL^{-1}**	***E. Coli* CFU.100 mL^{-1} or MPN.100 mL^{-1}**	**References**
Adelaide, Australia	Residential tanks	Aug. 2015 to Aug. 2016	<1 - ≥2,419	≥200	Chubaka et al., 2018
Southeastern Nigeria	Rainwater runoff from rooftops	Apr., Jul., and Oct. in 2022	ND-3.8×10^{6} (2.6×10^{6})	ND	Nwogu et al., 2024
Ekpoma town, Northern Ishan District of Edo state, South Nigeria	162 samples collected from different storage tanks in the community	Oct. to Dec. 2017	17×10^{6} - 38×10^{6}	40×10^{4} - 884×10^{4}	Tenebe et al., 2020
Southeastern part of Poland, near Rzeszów city, Poland	Non-industrialized area. Samples collected from direct atmospheric precipitation and roof gutters	Spring, summer, and autumn	few dozen to 6×10^{3*}	ND-50	Zdeb et al., 2021
Bulagi Utara, Indonesia	Rainwater harvesting	-	80-250	8-60	Sandy et al., 2024
Khulna and Bagerhat districts, coastal areas, Bangladesh	Sub-district areas, harvested rainwater	Mar. and Aug. 2009		Dry: < 1-900 (74) Wet: < 1-6,000 (288)	Islam et al., 2011
Selangor, Malaysia	Rooftop rainwater tanks	Nov. 2014 to Jun. 2015	1.03×10^{2} - 1.37×10^{5}	ND-1.64×10^{3}	Leong et al., 2017
Can Tho, Hau Giang, and Soc Trang provinces, Vietnam	Harvested rainwater	2011	max. at 102,500	-	Wilbers et al., 2013
Vinh Chau town, Soc Trang province, Vietnam	Harvested rainwater in a small urban	2010 to 2015	39	ND	Nguyen et al., 2019
Huong Hoa district, Quang Tri province, Vietnam	Harvested rainwater in an urban area	Oct. to Dec. 2017	-	ND	Nguyen, 2021
Cu Khe village, Thanh Oai district, Hanoi, Vietnam	23 samples in a peri-urban area	Aug. 2014 to Jul. 2015	10-12,000 (median: 270)	ND-3,200 (median: 8)	Lee et al., 2017
Hanoi city, Vietnam	Rainwater collected from direct atmospheric precipitation	May 2023 to May 2025	3,071 (ND-19,700)	266 (ND-5,300)	This study

Note: ND: Not detected; *: total number of bacteria at 37°C

3.4. Source and factors affecting FIB numbers in rainwater in Hanoi city

Both natural and anthropogenic factors are the primary drivers influencing the spread and persistence of FIB in the aquatic environment (Zhang et al., 2025; Liu et al., 2025).

3.4.1. Sources of FIB numbers in rainwater

Hu et al. (2017) reported that in urban

areas, anthropogenic factors can significantly affect the abundance of bacteria in rainwater. In this study, both Pearson's analysis and PCA results showed the positive correlation between population density and TC and EC numbers (Table 3; Fig. 3). The results of Pearson's analysis revealed that TC and EC numbers were slightly positively correlated with population density but negatively related to urban and/or agricultural lands (Table 3). In the PCA analysis, the first two principal components (F1: 56.7% and F2: 21.5%) accounted for 78.2% of the total variability, and separated the bi-plot into two parts, where TC and EC numbers and population density are on the left part and the lands of total surface, agriculture and urban are on the right one (Fig. 3). Moreover, all TC and EC values in inner-urban districts are notably situated on the left side of the bi-plot. All of this probably indicated the impact of high population density in inner-urban areas of Hanoi City on TC and EC numbers in rainwater samples. This was also demonstrated when considering the spatial variation of TC and EC numbers in rainwater samples (Fig. S2), where the mean FIB values at sites in inner districts were higher than those in suburban districts in Hanoi. These findings are consistent with the study reported by Anindita et al. (2025), which found that urban areas tend to exhibit higher contamination rates, often associated with dense human activity, inadequate waste management infrastructure, and industrial pollution. In addition, previous studies focusing on rainwater collected from different roof materials revealed that coliform sources stem from deposition by birds, small mammals, and airborne microorganisms on roof materials, and then on rainwater contained in tanks (Olaoye et al., 2012; Lee et al., 2017; Anindita et al., 2025). For example, Anindita et al. (2025) reported that rainwater in urban areas was contaminated by pigeon faeces, contributing to the spread of resistant *E. coli*. Other studies demonstrated that the presence of bacteria in rainwater can be explained by soil particles carried by the wind from agricultural fields fertilised with organic matter or local wildlife, mainly bird droppings, in the areas (Hamilton et al., 2019). Indeed, a previous study showed that bacteria present in wind-borne water droplets can travel up to 1 km and still retain their viability (Sánchez et al., 2015). Thus, for the case of rainwater in Hanoi, further studies on the presence of faecal streptococci and the value of FC/FS ratio, which may help to identify the coliform sources in rainwater in Hanoi, should be carried out in the following steps to confirm this theory. Moreover, source-tracking analysis is a potentially effective method to identify the sources of airborne bacteria. For example, Jiang et al. (2022) employed source-tracking analysis and found that soils, plants, human, and animal feces were the predominant sources of airborne bacteria in summer; however, unidentified sources were crucial in fall and winter in a typical rapidly developing city, Hefei, China.

Table 3. Pearson's results on the relationship between FIB numbers in rainwater, population density and land use in 22 districts of Hanoi city

Variables	**TC**	**EC**	**Pop.den.**	$\mathbf{S_{Tot}}$	$\mathbf{S_{Agr}}$	$\mathbf{S_{Urb}}$
TC	**1**					
EC	**0.346**	**1**				
Pop.den.	0.068	**0.142**	**1**			
S_{Tot}	**-0.147**	-0.122	**-0.586**	**1**		
S_{Agr}	**-0.156**	**-0.127**	**-0.547**	**0.991**	**1**	
S_{Urb}	-0.102	-0.122	**-0.617**	**0.939**	**0.927**	**1**

Noted that Pop.den: Population density; S_{Tot}: Total land area; S_{Agr}: Agricultural land area; S_{Urb}: Urban land area; Values in bold are different from 0 with a significance level alpha=0.05

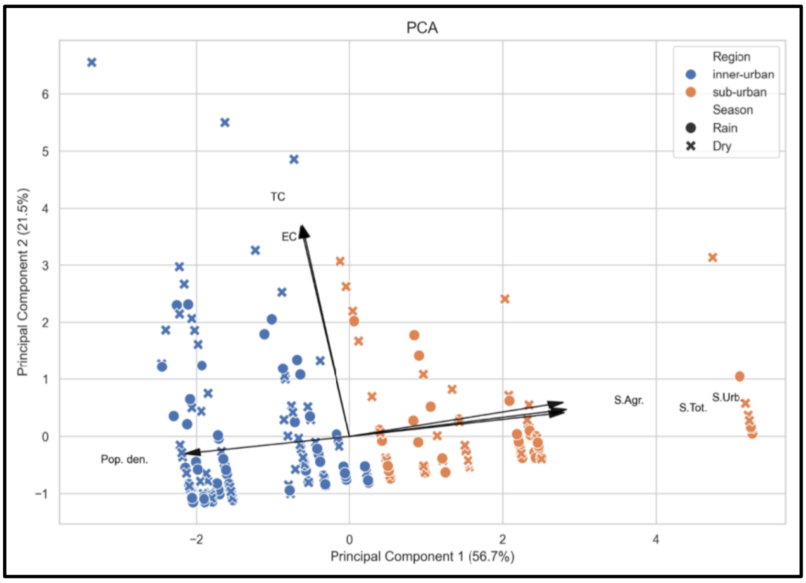

Figure 3. PCA results of FIB numbers in rainwater and population density, and agricultural land of 22 districts of Hanoi city

3.4.2. Meteorological factors impacted FIB numbers

Our results demonstrated that the mean values of all samples for both TC and EC numbers in the dry season were slightly higher than in the rainy season (Fig. 2). Indeed, FIB counts in the dry season and the first rainfall events in the rainy season in this study were more contaminated than in the samples collected in the middle and end of the rainy season. Previous studies have demonstrated that after the first rainfall flushes, FIB numbers and the concentrations of other water quality variables in harvested rainwater significantly decreased in the middle and end of the rainy season (Martin et al., 2010; Hamilton et al., 2019; Xing et al., 2019; Kraay et al., 2021). Thus, our results also revealed that the washout process of the initial rainwater events during the beginning of the rainy season, as well as the strong dilution effect of higher rainfall intensity in the rainy season, may affect FIB numbers in rainwater samples in Hanoi. In general, our study confirms that a combination of environmental factors of air pollutant levels, meteorological characteristics, and availability of microbial sources can drive seasonal and spatial variation of compositions and densities of microbial communities in the urban rainwater as well as the atmosphere, as reported for the case of Hefei city, China (Jiang et al., 2022).

3.5. Perspectives

The observed values of TC and EC collected at 22 districts in Hanoi City revealed a high potential health risk for residents who use rainwater for domestic purposes. Numerous studies have demonstrated that the consumption of untreated rainwater can pose a danger to public health (WHO, 2019; Nwogu et al., 2024; Anindita et al., 2025), and treatment methods should be applied before drinking if the TC numbers exceed 20 CFU.100 mL^{-1} (WHO, 2004). Thus, higher values of TC and EC numbers in this study revealed the need for effective measures to reduce fecal water contamination before using rainwater in Hanoi city. Anindita et al. (2025) recommended implementing effective treatment methods, such as filtration, chlorination, and UV radiation, to improve rainwater quality, making it suitable for multiple purposes. Additionally, the high numbers of TC and EC in raw rainwater observed in our study may highlight the importance of airborne microorganisms and other sources. Thus, further studies using microbial source tracking markers, as suggested by Denissen et al. (2021), or on the determination of the presence of faecal streptococci should be carried out to identify the sources of FIB presence in rainwater collected in Hanoi City.

On the other hand, rainfall and surface runoff have contributed to increased FIB contamination, transporting fecal matter from the land surface to receiving water bodies (Ahmed et al., 2019; Powers et al., 2020; Boithias et al., 2024). Indeed, some previous studies have reported that heavy rainfall can drive the increased levels of EC in drinking water sources and household water storage (Powers et al., 2023; Liu et al., 2025; Zhang et al., 2025), and even in bivalve molluscs when rainfall transports large amounts of bacteria into shellfish farming areas (Mudadu et al., 2023). Moreover, the synthesis of prior studies by Levy et al. (2016) revealed a clear correlation between rainfall, flooding, and diarrheal disease. Thus, high FIB numbers in rainwater, its transportations, and relationship with surface water sources, especially during the flood season, should be focused on for this region.

In this study, two variables, TC and EC, were measured to assess microbial water quality. More studies on the presence of other microbial pathogens (e.g., Salmonella, Enterococci, *C. perfringens, Bacteroides* spp.) should be conducted to assess the potential health risks associated with using harvested rainwater directly. In addition, other variables (e.g., toxic elements and persistent substances) that can be washed and transported from the atmosphere (Archundia et al., 2025) should also be examined to ensure the safe use of rainwater for domestic purposes.

Finally, our study has focused on rainwater sampled only in Hanoi. Expanding the sample numbers in a larger region related to meteorological data and human activities may reveal more details of factors affecting microbial contamination in developing countries like Vietnam.

4. Conclusions

FIB numbers in rainwater collected at 22 sites in inner-city and suburban districts of Hanoi City were investigated in both the rainy and dry seasons from 2023 to 2025. The mean values of TC and EC in raw rainwater at most observed sites exceeded the limits of the Vietnam national technical regulation for domestic water use and also the WHO guideline (2022) for drinking water. Thus, our results revealed the high public health risk and the need for preventive and treatment measures implemented to mitigate the risks associated with using harvested rainwater.

The results demonstrated an apparent spatial variation of FIB numbers in rainwater samples in Hanoi, with higher values detected in inner-urban districts where high population densities were found. Both natural and anthropogenic factors influenced the spread and persistence of FIB in this study. However, the details of microbial sources in rainwater in Hanoi city need further investigation.

Besides, our study provides data on FIB numbers in rainwater in only Hanoi city. Further observations on a larger scale and over a more extended time period, together with meteorological characteristics, are needed to fully assess the spatial and temporal variation of microbial contaminations in wet deposition in Vietnam. The present study, however, partly provides scientific significance for implementing policies on air environmental protection in Hanoi, as well as in other large cities in developing countries in Asia.

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APPENDIX

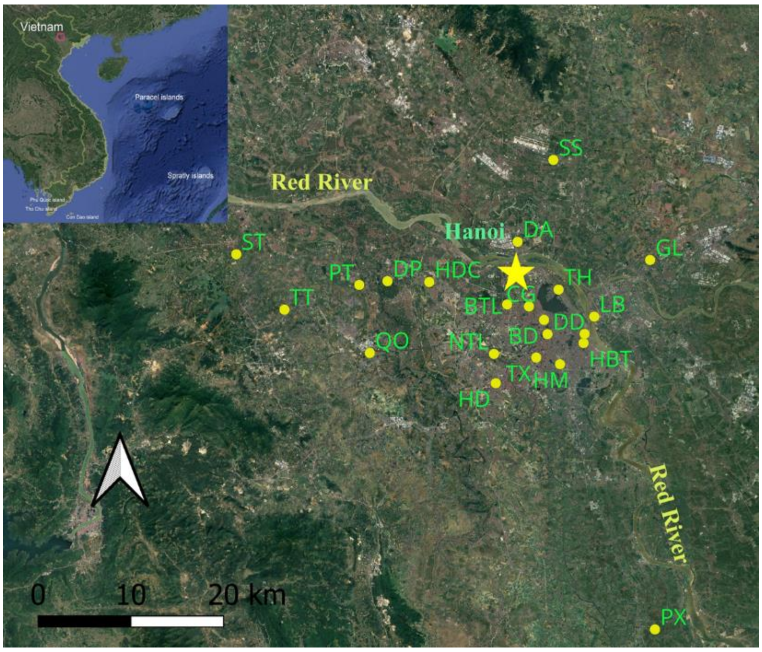

Figure S1. Rainwater sampling at 22 sites in inner and sub-urban districts of Hanoi city

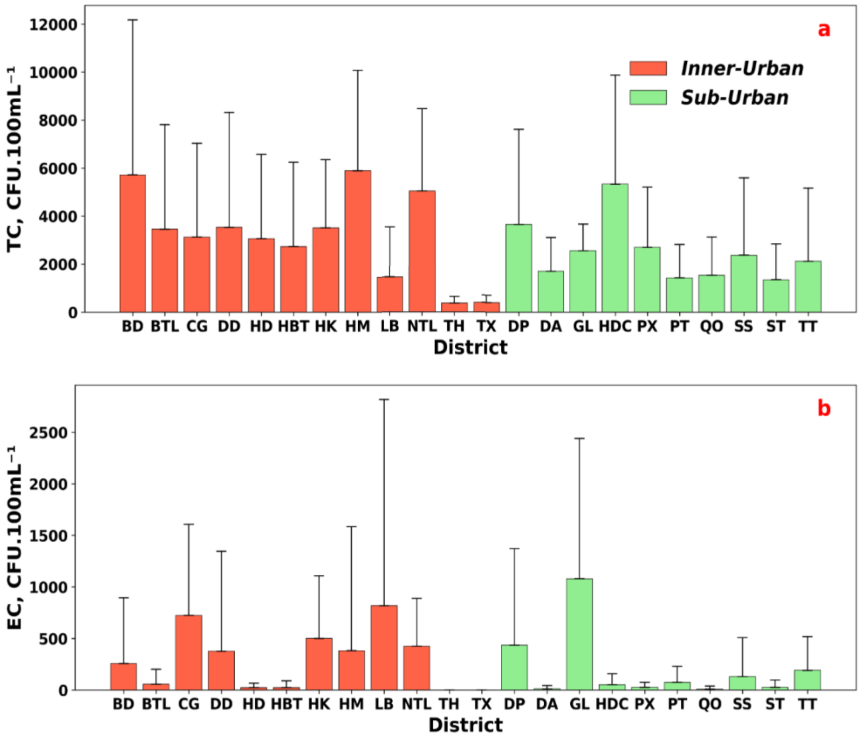

Figure S2. Mean values of TC (a) and EC (b) numbers in rainwater samples at 22 sites in Hanoi city