Environmental Challenges 22 (2026) 101443

Contents lists available at ScienceDirect

Environmental Challenges

journal homepage: www.elsevier.com/locate/envc

The potential of collected rainwater as an alternative water resource for domestic purpose to mitigate groundwater overexploitation in terms of water quality and people's acceptance

Van Cam Pham [a,*], Johannes Ho [b], Jonas Bauer [a], Nicolas Börsig [a], Felix Dörr [a], Tran Viet Hoan [a,c], Elisabeth Eiche [a], Andreas Tiehm [b], Stefan Norra [d]

[a] Karlsruhe Institute of Technology (KIT), Institute of Applied Geosciences, Adenauerring 20b, 76131 Karlsruhe, Germany
[b] TZW: DVGW-Technologiezentrum Wasser, Department of Water Microbiology, Karlsruher Straße 84, 76139 Karlsruhe, Germany
[c] National Center for Water Resources Planning and Investigation (NAWAPI), No. 93, lane 95, Vu Xuan Thieu Street Sai Dong Ward, Long Bien District, Hanoi, Vietnam
[d] Potsdam University, Institute of Environmental Sciences and Geography, Soil Sciences and Geoecology, Campus Golm, Building 12, 14476 Potsdam - Golm, Germany

ARTICLE INFO

Keywords:
Groundwater overexploitation
Alternative water resource
Water management
Rain water harvesting
Water quality
Mekong Delta

ABSTRACT

Ca Mau province, located in the south of the Mekong Delta, is strongly affected by land subsidence and seawater intrusion. Overexploitation of groundwater has been highlighted as a significant driving factor for these processes. As groundwater currently plays a crucial role in the local water supply, this study examines the potential of rainwater as an alternative water source for domestic use to reduce groundwater extraction and contribute to ensure the safe and sustainable water resource for public use (SDG 6). The present study follows a multidisciplinary evaluation of the potential of rain water as an alternative water resource, covering an assessment of (i) social perception of rainwater usage, (ii) rainwater availability as well as water quality analyses of rainwater stored under various conditions. For this, a combined survey and sampling campaign throughout Ca Mau province was conducted in two main phases between 2019 and 2022. The survey includes a questionnaire which was completed by 473 participants together with in-depth interviews in several selected locations. Complementary, time series of precipitation were analyzed to determine the potentially available rainwater quantity. Stored rainwater samples were collected and analyzed according to their quality based on physical parameters, chemical parameters using ICP-MS and Ion Chromatography with 49 water samples and biological parameters using the IDEXX Colilert® system and MALDI-TOF-MS with 75 water samples. Based on the results, factors that could affect the quality of rainwater were examined. The results show that in some rainwater samples, threshold values of the standards from Vietnamese regulation were exceeded for some parameters, raising the issue of rainwater treatment before use. The questionnaire revealed that rainwater is considered as a potential water source which can replace groundwater for domestic purposes by participants. Despite concerns about rainwater storage during the dry season, public acceptance of using rainwater is generally high. However, the government's interest in communicating information about current environmental issues as well as support in guiding rainwater storage and economic support during the transition process is an issue that people are concerned about. The results of this study provide new insights to further identify potential pilot sites in Ca Mau for rainwater harvesting as an alternative to groundwater extraction, as well as to design concepts for optimizing the use of rainwater.

1. Introduction

The Mekong Delta, the third largest delta in the world, is facing severe land subsidence, for which groundwater over-extraction is considered the major driver (Minderhoud et al., 2020). The effect of land subsidence is exacerbated by sea level rise and progressive seawater intrusion into the delta (Bauer et al., 2025). Besides, human activities, including sand mining and regulation of the Mekong river (reservoirs and dams), cause a substantial decline of sediment supply further accelerating land subsidence (Zoccarato et al., 2018). The Vietnamese

* Corresponding author.
E-mail address: van.pham@kit.edu (V.C. Pham).

https://doi.org/10.1016/j.envc.2026.101443
Received 24 December 2025; Received in revised form 18 February 2026; Accepted 24 February 2026
Available online 26 February 2026

Mekong Delta has the highest population density in the area with 297 inhabitants per km^2 and is home to around 19.8 million people (Mekong River Commission , 2019). Accordingly, people's demand in water in this area is high. Residents mostly use groundwater for their daily need. For example, in Can Tho province, people use groundwater for many activities such as cooking, drinking and even for washing, bathing and gardening (Danh and Khai, 2015). Similarly, in coastal provinces like Ca Mau province (CMP), groundwater is the main water source used for all purposes including washing, gardening, cooking and drinking (Pham et al., 2023). Because of the high demand, groundwater is extracted uncontrolled without any planning. Of the total 175,710 wells counted in 2017, only 248 wells served centralized drinking water production and only 452 private wells had an abstraction license. The majority of wells were private wells without any license for operation (Pechstein et al., 2018). Groundwater extraction rates from small to medium sized private wells in CMP was around <200 m^3/day (Pechstein et al., 2018). In 2015, the groundwater extraction required to meet the freshwater demand was 0.42 million m^3/day (Pechstein et al., 2018). Hoan et al. (Hoan et al., 2022) revaluated that the groundwater exploitation rate in the Ca Mau Peninsula is approximately 567,364 m^3/day, with the highest abstraction occurring in the upper–middle Pleistocene (qp_{2-3}) and middle Pliocene (n_2^2) aquifers. Bauer et al. (Bauer et al., 2022) indicated that the hydrogeological layers in the Ca Mau Peninsula are hydraulically connected, suggesting that salinization from seawater intrusion or other sources, driven by altered aquifer conditions, may accelerate groundwater degradation. This situation has caused a series of environment challenges in CMP and residents have to cope to many issues arising from groundwater extraction. In particular, significant land subsidence is challenging the low elevated CMP with ongoing subsidence rates of 2–4 cm/year derived from satellite data evaluation (Erban et al., 2014; Dörr et al., 2024) and from on-site measurements (Karlsrud et al., 2017; Dörr et al., 2023). The deep aquifers, which are used most frequently for groundwater extraction, have a low land rebound potential and therefore an insignificant subsidence mitigation potential (Dörr et al., 2025). Groundwater resources are significantly impacted by climate change and hydrological variables (Bui et al., 2017). To ensure sustainable groundwater development, groundwater abstraction should be limited, and groundwater quality should be improved through additional artificial recharge measures (Bui et al., 2017).

In addition, current research shows that groundwater quality in large parts of the Mekong Delta lowland is unsuitable for drinking and irrigation and may lead to long-term non-carcinogenic health effects (Tran et al., 2021). The use of pesticides has led to large-scale problems of surface water contamination, which also has spread to other water sources such as groundwater (Chau et al., 2015). Moreover, specific land use can affect the salinity of shallow aquifers (Hoan et al., 2025). In the rural areas of the Mekong Delta, shallow groundwater is commonly utilized as a drinking water source to replace contaminated surface water (Buschmann et al., 2008). Analysis of several water samples revealed that arsenic and manganese concentrations exceeded the World Health Organization (WHO) guideline values in some areas of the Mekong Delta, potentially leading to chronic poisoning and posing significant risks to human health (Buschmann et al., 2008). There is the possibility that groundwater quality of private tube-wells built before 1975 was better than that of groundwater wells which were recently built (Danh and Khai, 2015). In the context of groundwater over-extraction and the decrease of groundwater quality (Erban et al., 2014; Buschmann et al., 2008), the identification of potential alternative water sources is of great relevance for the study area.

In this study, rainwater is considered as a potential substitute for domestic purposes, which was demonstrated in previous studies worldwide. Rainwater harvesting is practiced in other parts of Southeast Asia and is considered a potential option for local residents, depending on its availability (Özdemir et al., 2011). Rainwater utilization has long history as a drinking water source in rural areas of Vietnam. It is considered a good-quality source of drinking water that is both cost- and energy-efficient (Nguyen et al., 2019). Rainwater harvesting is considered a suitable approach for freshwater supply and management and has, for example, been increasingly adopted across Europe (Wartalska et al., 2024). However, based on the financial situation and specific social characteristics in CMP, the utilization of rainwater for domestic purpose as well as people acceptance need further investigation. Characteristics of household's head (including age, sex, education status and time of settlement) are important factors impacting to their probability of changing the water source (Danh and Khai, 2015). The objective of this study is to assess current rainwater use practices in CMP and to evaluate whether rainwater could serve as an alternative water source to reduce groundwater extraction.

2. Methodology

2.1. Study area

This research was conducted in CMP, the southernmost province in Vietnam. The area covers around 5270 km^2 (General Statistics Office, 2023). CMP has three sides bordering the sea and a dense network of canals connected to the ocean through major river mouths. The elevation is below 0.8 m in 2018 (Minderhoud et al., 2019), with limited freshwater inflow from upstream, resulting in widespread salinization across much of the region (Ca Mau, 2018).

Please note that this work uses the pre-2025 provincial terminology and administrative boundaries, as provinces were substantially restructured in 2025. There are nine districts in CMP with a total population of around 1.2 million people (General Statistics Office, 2022). According to the Statistics Office (General Statistics Office, 2023), the average population density in CMP is 229 persons/km^2. The ratio of male and female is 104.5 male/100 female. The population in urban areas is 275,812 people which accounts for 22.8 % of the total population, compared with the population in rural area where 931,766 people live which equals a share of 77.2 %. The main occupation of CMP residents is high and mid - level professionals, clerks, personal services, workers, sale workers, skilled agricultural, forestry and fishery workers or have unskilled occupations (General Statistics Office, 2023).

Under the effect of the tropical monsoon climate, CMP has two distinct seasons, which are the dry season and the rainy season. Significant rainfall mainly occurs in the rainy season from May to November with the total amount of 2413.4 mm, while the dry season lasts from December to April with relatively little amount of precipitation with 505.1 mm in 2022 (General Statistics Office, 2023). The water demand is extremely high even though the water sources are limited. The current freshwater supply sources in CMP are groundwater, tap water and bottled water (produced mainly from groundwater) and rain water (Pham et al., 2023; Vinh et al., 2024). However, given that tap water (water distributed by water supply station) is not available for the whole area, some people do not really have the opportunity to use this water source and tap water is originated from groundwater after treatment in some places (Pham et al., 2023). Surface water is not used due to high salinity and pollution resulting from land use practices, particularly extensive shrimp farming and wastewater (Van Muoi et al., 2022).

2.2. Questionnaire collection and analysis

In order to assess the acceptance of using rain water as an alternative water resource, two surveys in two main phases between 2019 and 2022 were conducted. Questionnaires were collected during the face-to-face interviews between the corresponding author, instructors and surveyed households in different locations in CMP. The questionnaire was first introduced in 2019 and revised in subsequent versions in 2021 and 2022 based on the initial interview results. For the first survey campaigns in 2019 and 2020, questionnaires were deployed across all nine districts in CMP with the content focusing on the importance of groundwater, the potential of available water sources and people's awareness of land subsidence. 144 questionnaires were implemented together with the collection of groundwater samples at the same location, providing an initial comprehensive overview of the study area (Pham et al., 2023). Afterwards, in 2021 and 2022, subsequent surveys were conducted based on the results of the first campaigns. During this period, 329 participants were interviewed in eight districts of CMP, resulting in a total number of interview participants to 473. To ensure the representativeness, the Yamane's formula for calculating sample size was applied (Yamane, 1973; Ahmed, 2024):

$$n = \frac{N}{1 + N(e)^2}$$

N: population e: standard deviation n: number of samples to reach the level of representativeness

Based on the information provided by the general statistics office (General Statistics Office 2022), the number of samples needed for representativeness is around 400.

Thus, the number of interview participants during field trips meets the conditions to represent the region. During the second field trip, the number of questions in the questionnaire was increased to 62 questions in order to capture people's opinion in greater detail by broadening the research topics addressed. The questionnaire consisted of six parts, including general information of respondents, importance of groundwater, importance of water supply, potential use of rainwater, potential use of surface water and people's awareness about the problem of land subsidence in CMP. This study focuses on the information gathered that is related to the potential for using rainwater for households, especially in exchange to using groundwater. The questions with regard to satisfaction with using other water sources instead of groundwater and people's self - evaluation of rain water quality were evaluated in this study. The answer options were divided into five levels (Likert scale) with the level of satisfaction gradually increasing from 1 (people don't want to replace groundwater under any circumstances) to 5 (people are highly motivated to substitute groundwater or are already doing so). Respondent's perceptions of rainwater quality were categorized into five levels, ranging from level 1 (lowest quality) to level 5 (highest quality). After completing the questionnaire, the interviewer as well as the author of this study had an in-depth discussion about the reason behind the answers, therefore this study provides also information on the related context of people's opinions.

In parallel with the questionnaire, 49 stored rainwater samples were collected randomly at the interview locations to evaluate the people's opinions of using rain water together with the quality of rainwater at the current locations as well as figure out a relationship between usage habits and people's assessment of rainwater quality in term of physicochemical parameters. Moreover, for collected rainwater, hygiene issues are very important when people use it for drinking purposes. Therefore, the number of samples collected to evaluate the microbiological quality was even higher (74 samples).

Similar with the methodology used in the previous study (Pham et al., 2023), the survey and questionnaires were evaluated with regard to various aspects including quantitative and qualitative assessments. For the quantitative approach, answers to questions related to quantity such as the number of people using water in the household, the maximum amount of rainwater stored in the household, etc. were statistically evaluated. For the qualitative approach, answers related to people's subjective perception are mentioned, for example the purpose of water use, the level of people's interest for different water sources as well as the level of people's satisfaction with changing water sources, etc. The multi-dimensional approach allows the authors to capture the different points of view of the interview participants, as well as the overall context.

The primary data set from the 2019 and 2020 survey provided general information and an overview of the research area, leading to the selection of focused locations for the next survey. Based on the initial results with data analysis from general to in-depth details in 2019, together with people's opinion, groundwater quality in the southern of CMP was getting salinized. Tapwater was distributed by centralized water stations and supplied for households in southern area. It's a reason why the next surveys were only focused on the northern and central of CMP. The distribution of survey questionnaires is shown in Fig. 1. The questions dug deeper into the potential of each type of water, current usage status and people's opinion for each option.

2.3. *Water sample collection and analysis*

2.3.1. *Water sampling and chemical analysis*

In this study, rainwater samples were collected from selected households participating in the survey. Rainwater was collected directly at the respective water storage vessels and tanks of the households participating in the survey. Physicochemical parameters, such as pH, electrical conductivity (EC) and temperature were measured onsite using a portable multi parameter meter (WTW Multi 3630 IDS). In addition, the rainwater samples were taken and preserved for chemical analysis in the laboratory. The procedure of sample collection and preservation was similar to the way described in our previous publications for groundwater samples (Pham et al., 2023; Bauer et al., 2022). For cation analysis, 50 μL of high purity nitric acid was added to the samples to prevent metal precipitation (W. E. APHA AWWA, 2005), while for anion analysis, 50 μL of sodium azide was added to prevent microbial growth (Vanderford et al., 2011). Cations were analyzed using ICP-MS (Thermo Fisher X-Series 2 and ICap RQ) and anions with Ion Chromatography (Dionex ICS-1000 with column IonPac As Supressor ERS 500 and Methrom Compact IC 930 with column Metrosep A Supp 5–150) at the Laboratory for Environmental and Raw Material Analysis at the Institute of Applied Geosciences at the Karlsruhe Institute of Technology (Bauer et al., 2022).

Following the analysis, the rainwater quality was compared with the National Technical Regulation on Domestic Water Quality QCVN 01–1/2018 BYT (the regulation was applied for domestic water quality and people used it as standard when this research was carried out) and the newest updated version QCVN 01–1/2024. In the updated version of 2024, the threshold of some parameters have been adjusted. Of the parameters mentioned in the National Technical Regulation on Domestic Water Quality QCVN 01- 1/2018 BYT and QCVN 01–1/2024 BYT, the following parameters were used in this study: pH, EC, NH_4^+, Cr, As, Cd, Sb, Pb, Al, Mn, Zn, B, Fe, Ba, Na, Ca, Cl^-, SO_4^{2-}. The parameters are characterized by the fact that humans can recognize abnormalities when water concentrations exceed certain thresholds (WHO, 2022). For instance, at levels above 5 mg/L, cooper (Cu) can impact color of the water and cause undesired bitter taste. At levels above 0.3 mg/L, iron (Fe) can stain laundry and sanitary fixtures. At levels above 0.02 mg/L, manganese (Mn) can form insoluble manganese oxides in water supplies and may cause discolored water and staining like iron (Fe). When concentrations of zinc (Zn) exceed 3–5 mg/L, it may cause a greasy film when water is boiled. In addition, sulfate can cause noticeable taste. Taste thresholds range from 250 mg/L for sodium sulfate and 1000 mg/L for calcium sulfate (WHO, 2022). Statistical evaluation, data processing and visualization were performed with Origin 2022b software.

2.3.2. *Water sampling and micro-biological analysis*

Samples were collected in sterilized 50 mL plastic bottles (VWR International GmbH, Darmstadt, Germany) and stored cooled (4 °C) until shipment. After completion of the sampling campaign, all samples were transported under cooled conditions to Germany and subsequently analyzed at the TZW German Water Centre Laboratory. Rainwater storage samples were analyzed for *Escherichia coli*, coliform bacteria and enterococci. Enumeration of *E. coli* and total coliform bacteria was performed using the IDEXX Colilert® system (IDEXX Laboratories, Inc., Westbrook, ME, USA) according to the manufacturer's instructions.

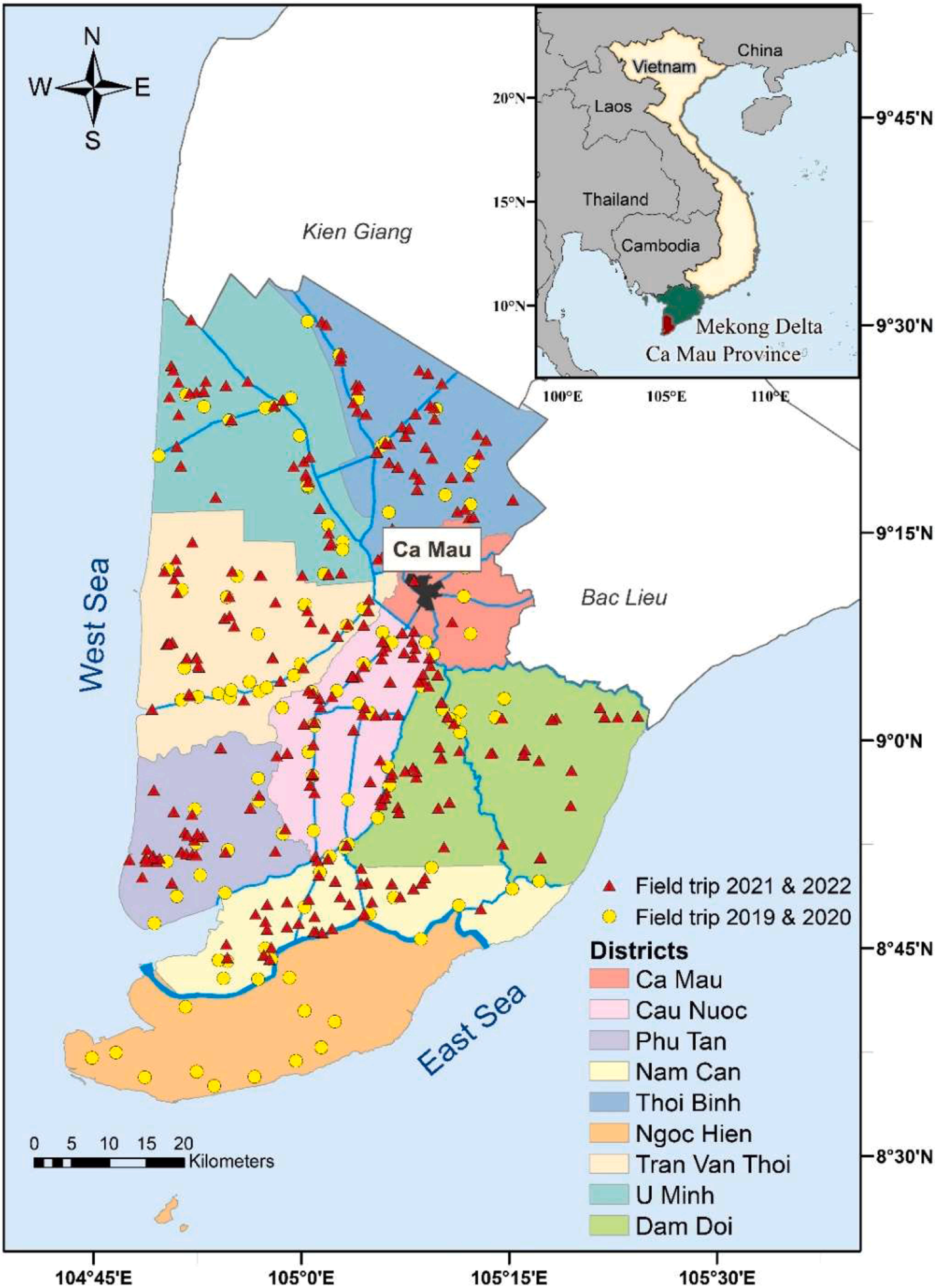

Fig. 1. Map of questionnaire location in Ca Mau province.

Enterococci were quantified using the IDEXX Enterolert® system (IDEXX Laboratories, Inc., Westbrook, ME, USA). For confirmation and further identification, up to 15 wells per sample were picked with sterile tips and analyzed using MALDI-TOF-MS (Microflex LT, Bruker Daltonics GmbH, Bremen, Germany) as described previously (Reitter et al., 2021). Relative species frequencies were obtained by normalizing species counts to the total number of identified isolates. Statistical evaluations were performed using Python 3.11. The Kruskal–Wallis test (scipy.stats.kruskal) was used to assess differences in microbial concentrations across roof types, and chi-squared tests (scipy.stats.chi2_contingency) were applied to evaluate species composition and detection frequencies. Data processing and visualization were conducted using pandas (v2.2.2), numpy (v1.26.4), matplotlib (v3.9.1), and seaborn (v0.13.2).

3. Results

3.1. Current state of rainwater storage in Ca Mau and people’s habit in using rainwater

It was found that people use different ways to store rain water and use rain water for different purposes. The containers for storing rainwater of the majority of people interviewed in 2019 were mainly ceramic tanks with covers (with 52.8 % of respondents). Besides, 21.5 % of respondents used plastic tanks and 11.8 % people used concrete tanks. Only 3.5 % of people did not use any covers when storing rainwater in ceramic tanks and 20.1 % of people participating in the survey used rainwater directly without long term storage. They took rainwater that is collected in a small basin after heavy rain (Fig. 2). In addition, the survey results provide insights into the role of rainwater in people's lives. People use rainwater for multi-purposes. 72.9 % of people participating in the survey use rainwater for drinking, while 56.3 % of people utilize rainwater for cooking. Only 6.3 % of people use rainwater for cleaning and washing purposes (Fig. 3).

From this initial information about the potential of using rainwater, the second survey was conducted and focused on rural areas of 8 northern districts in CMP (Fig. 1). A total of 329 people participated in the survey, of which 62.0 % of respondents were men and 38.0 % were women. Respondents' ages range from 19 to 85 years, with the average age of survey participants being 47 years. The occupations of the interviewees were very diverse. Because the research area is concentrated in rural areas, the majority of people working as farmers account for 53.5 %, followed by small household businesses (grocery shop, car washes etc.) with 22.8 %. The remaining people are carrying out occupations such as officers with 12.2 %, or are workers with 5.8 %, housewives with 3.0 %, retired with 1.8 % and unemployed person with rates of 0.3 %. Similar to the information from 2019, people in CMP usually have more than one source of income (Pham et al., 2023). Based on 329 interviews, the average household income is around 9 million VND per month (around 341 USD per month). In 2021, 53.2 % of interviewees use plastic tanks to store rainwater, while 48 % of people use ceramic tanks with cover (Fig. 4). 64.7 % of respondents use rainwater for drinking purposes, while 52.6 % and 59.6 % of respondents use rainwater also for both washing and cooking purposes (Fig. 5).

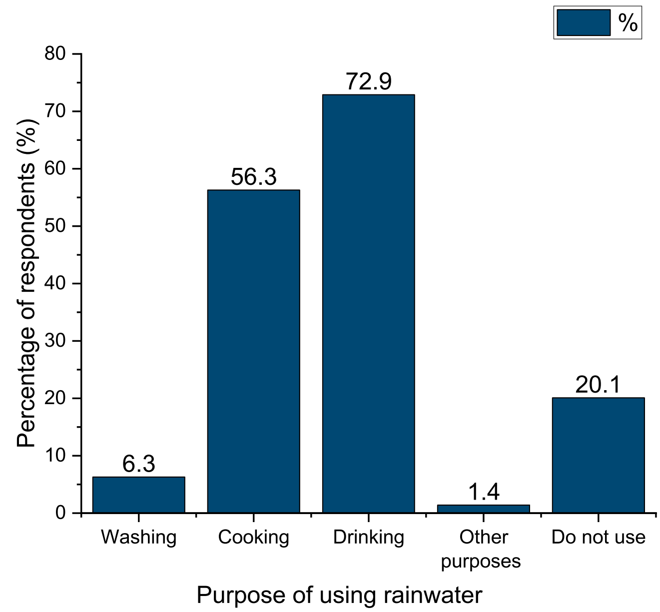

Fig. 3. Purpose of using rainwater in CMP (data from field trip in 2019, $n = 144$).

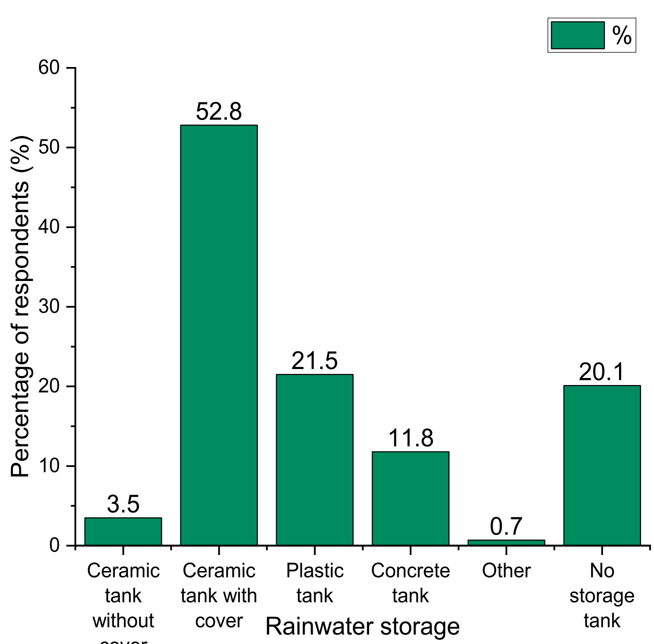

Fig. 2. Types of devices used for rainwater storage in CMP (data from field trip in 2019, $n = 144$).

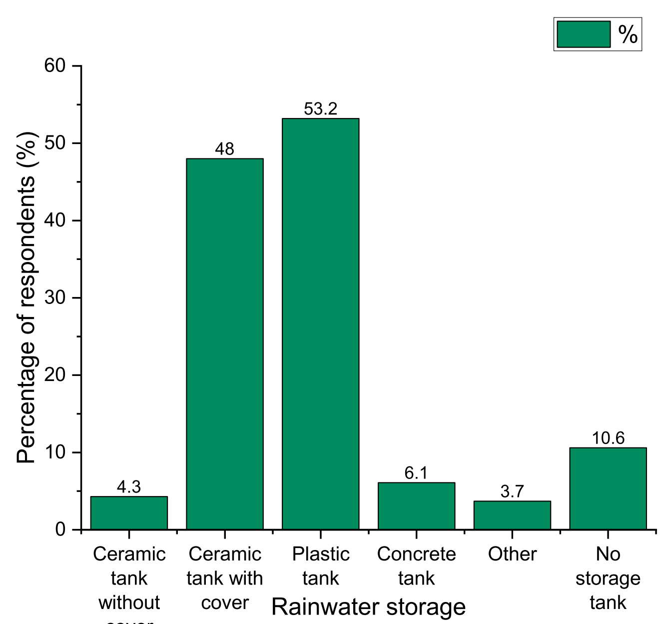

Fig. 4. Types of devices used for rainwater storage in CMP (data from field trip in 2021, $n = 329$).

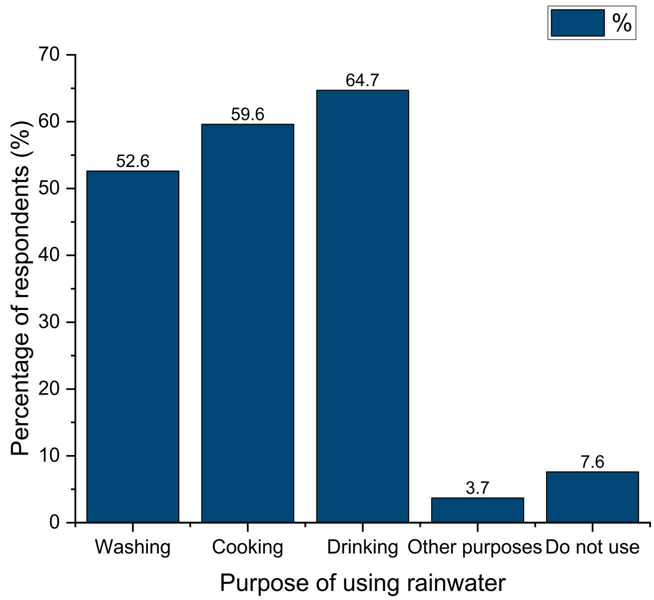

Fig. 5. Purpose of using rainwater in CMP (data from field trip in 2021, $n = 329$).

After determining the changes of rainwater storage habits and rainwater using purposes in the 2021 survey, information surrounding the state of using rain water was further investigated. The capacity of storing rainwater depends on the available storage facilities at their home. With the responses from 329 households, the current average amount of rainwater stored by each of them is around 2.5 m^3 per year. Rain water is mainly collected via roof systems with 98.3 % of the people who answered the questionnaire. Rainwater has been used for a long time and based on people's experience, rainwater is collected from the roof only after discharging the first few rains of the season. According to information from discussion with households, the first rainwater of the season is not collected but used to clean the roof from dirt and impurities. After that, rainwater is collected through pipe systems in tanks. In many households, different roof materials are used in house constructions. Regarding the results obtained from the latest survey in 2021/2022, before using, most people use different measures to treat and improve water quality such as settling, filtering through cloth, boiling and using filtration systems (Table 1).

57.9 % households who do not treat rainwater use this source exclusively for washing and gardening purposes. 71.1 % of those who do not apply any forms of treatment for rainwater refrain from using rainwater for drinking. For the group of household who use common and cost-effective treatment such as settling, filtration via cloth or boiling, 89.5 % people utilize treated rainwater for cooking and direct consumption. Furthermore, 100 % of respondents who apply filtration systems consume rainwater for both cooking and drinking purpose while 90 % of this group use treated rainwater specifically for drinking purpose.

Table 1
Rainwater treatment options used in Ca Mau province. results compiled in the survey in 2021/2022.

Rainwater treatment methods	Percentage of households using this treatment
No treatment	11.6 %
Settling	55.3 %
Basic filtration via cloth	41.3 %
Boiling	44.4 %
Mini filtration system	3.7 %
Other treatment	0.9 %

3.2. Evaluation of collected rainwater quality

3.2.1. Chemical quality of rainwater

Collected rainwater samples were analyzed, objective parameters like legal regulations (the Vietnamese regulation QCVN 01–1:2018/BYT and QCVN 01–1:2024/BYT) on domestic water quality standards (Table 2) have to be used for quality evaluation.

According to the results shown in Table 2, most parameters are below the thresholds of QCVN 01–1:2018 and QCVN 01–1:2024. Overall, inorganic quality of rainwater is therefore appropriate for drinking water or other domestic use. However, there are three parameters whose values partially exceed the allowable thresholds in QCVN 01–1:2018, which are pH, nitrate and aluminum (Al) (Fig. 6). With the new updated regulation in 2024, the threshold of Nitrate is higher, for this reason, some samples which had exceeded the threshold in 2018, have become acceptable in 2024. Measured aluminum (Al) concentrations however exceed the allowable thresholds in both regulations.

In total 49 rainwater samples were analyzed, including 10 samples harvested from asbestos tiles/fibre-cement roofs, 37 samples from galvanized steel sheet roof systems and 2 samples from thatch roofs. This categorization reveals that samples exceeding the QCVN standard in 2024 for Al is in the group representing samples harvested from the galvanized steel sheet roof (Fig. 7). For further investigation, values of Al were statistically evaluated to figure out the connection with roof type category. The Kruskal-Wallis test is applied, results ($p = 0.33 > 0.05$) showing that there are no statistically significant differences between three different types of roof. Regarding the impact of the storage technique, it could also be demonstrated that collected rainwater samples from the ceramic tank with a cover and plastic tank currently exceed the standard of aluminum concentration of some samples (Fig. 7). However, a similar statistically equation was applied to Al concentration values in different water storage category. The Kruskal-Wallis test was implemented and resulted in $p = 0.62{,}781 > 0.05$. Thus, there is no significant difference between different water storage tanks (ceramic tank without cover, ceramic tank with cover, plastic tank and concrete tank).

3.2.2. Microbiological quality of rainwater

Together with the chemical parameters listed in chapter 3.2.1, microbiological contaminants are crucial parameters regarding water quality. Indicator organisms such as *E. coli*, enterococci, and coliform bacteria express possible contamination and the potential presence of pathogenic microorganisms (WHO, 2022). Threshold values for these microbial indicators are specified in Vietnamese national regulations (2018 and 2024) for domestic water, covering drinking, cooking and hygiene purposes Table 3.

Coliform bacteria showed the highest concentrations among the analyzed indicators, with maximum values up to around 5×10^5 MPN/100 mL and a mean of approximately 3×10^4 MPN/100 mL, with a detection rate of 75 % (Fig. 8). Enterococci were detected less frequently, with maximum counts of 9×10^2 MPN/100 mL and a positive rate of 43 %. In contrast, *E. coli* was rarely detected (7 % of samples), likely due to the prolonged storage (up to 14 days at 4 °C) and transport to Germany before analysis. *E. coli* is commonly used as a short-term indicator of recent fecal contamination (WHO, 2022) and microbiological water samples should ideally be analyzed within 24 h to avoid underestimation of indicator bacteria (Canada, 2024). To improve the precision of *E. coli* measurements and avoid die-off effects, we recommend on-site microbiological testing within 24 h in Vietnam; however, this was not logistically feasible in our study.

When comparing samples from different roof materials, microbial concentrations exhibited high variability and no consistent trend indicating differences between roof types was observed. This was confirmed by Kruskal–Wallis test results ($p > 0.05$), indicating no statistically significant differences among roof categories (Fig. 8). An analogous analysis across storage types (ceramic tank with cover/without cover,

Table 2
Comparison of rain water quality with threshold values that are compiled in the Vietnamese regulations QCVN 01–1:2018 and QCVN 01–1:2024.

Parameter (unit)	Unit	Concentration				QCVN 01–1:2018/BYT	QCVN 01–1:2024/BYT
		Min	Max	Median	SD		
pH		4.7	9.1	7	0.99	6–8.5	6–8.5
As	µg/L	0.06	1.46	0.24	0.28	10	10
B	µg/L	1.10	54.1	10.4	10.9	300	2400
Sb	µg/L	0.04	0.38	0.05	0.08	20	20
Ba	µg/L	0.35	66.0	3.24	13.1	700	1300
Cd	µg/L	0.002	2.17	0.01	0.33	3	3
Pb	µg/L	0.01	2.31	0.08	0.35	10	10
Cl^-	mg/L	0.45	17.1	3.26	3.76	250 (300)	250 (300)
Cr	µg/L	0.04	3.87	0.27	0.64	50	50
Cu	µg/L	0.11	4.53	0.64	1.06	1000	1000
Ca	mg/L	0.18	36.0	3.48	7.83	120	120
F	mg/L	0.01	0.05	0.02	0.01	1.5	1.5
Zn	µg/L	5.10	905	67.3	252	2000	2000
Mn	µg/L	0.18	27.3	2.01	4.79	100	100
Na	mg/L	0.29	23.94	1.72	5.14	200	200
Al	µg/L	1.81	387	27.4	74.6	200	200
Ni	mg/L	0.07	1.75	0.21	0.42	70	70
NO_3^-	mg/L	0.18	7.17	1.4	1.42	2	11
Fe	µg/L	1.33	47.6	5.76	7.12	300	300
SO_4^{2-}	mg/L	0.28	13.3	1.34	3.16	250	250

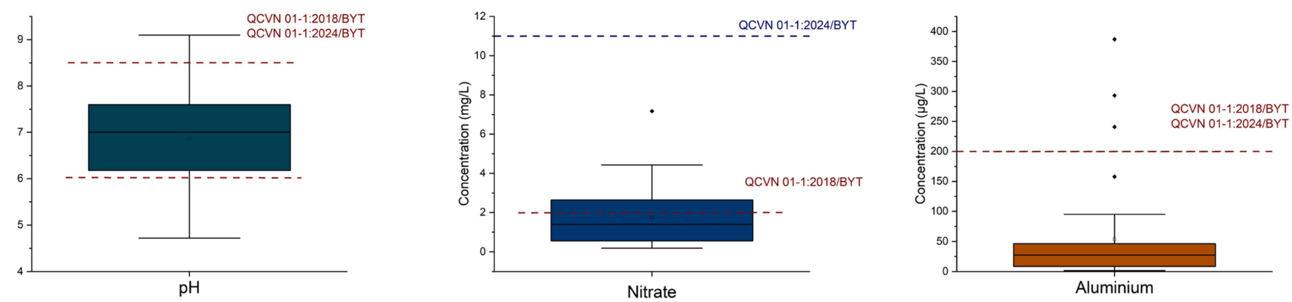

Fig. 6. Concentrations and distribution of water parameters in samples that are partially above the thresholds of QCVN 01–1:2018/BYT and QCVN 01–1:2024/BYT.

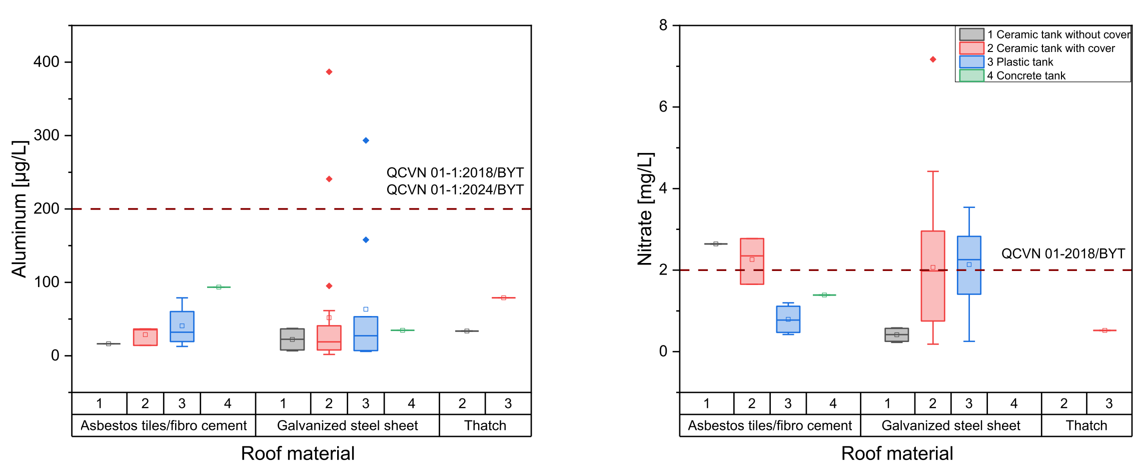

Fig. 7. Concentration and distribution of the parameters aluminum, nitrate in samples representing different roof materials and water storage techniques.

plastic, concrete) likewise yielded no statistically significant differences in concentrations of coliforms, or enterococci after multiple-testing correction (Kruskal–Wallis, $p > 0.05$ for all pairwise comparisons). For *E. coli*, a Kruskal–Wallis comparison yielded a nominally significant p-value ($p = 0.02$) (Fig. 9). However, this result is not considered interpretable, as almost all groups consisted exclusively of non-detects. In a more detailed analysis, all storage-type and roof-material groups were jointly evaluated, yielding similar results without significant differences (Fig. S1 in supplementary material).

MALDI-TOF-MS analysis identified various coliform species (Fig. 10) in rainwater tanks, with *Enterobacter cloacae* and *Klebsiella pneumoniae* dominating across roof types. Additional species such as *Serratia marcescens* and *Citrobacter freundii* occurred only in samples from metal roofs. The two samples from thatched roofs contained exclusively *Enterobacter asburiae*. However, this finding remains exploratory due to the very small sample size.

Statistical analysis revealed no significant differences in species composition between roof types after correction for multiple testing.

Table 3
Comparison of microbiological water quality standards for different uses according to Vietnamese QCVN regulations. "Not specified" indicates that no explicit limit is provided in the respective guideline.

Parameter	Positive rate,mean, min, max	QCVN 01–1:2018/BYT	QCVN 01–1:2024/ BYT
E. coli	**7 %** **9 MPN/100 mL** 5–15.5 MPN/100 mL	< 1 CFU/100 mL	<1 CFU/100 mL (must not be detectable)
Total Coliforms	**75 %** **30.000 MPN/100 mL** 5–500.000 MPN/100 mL	< 3 CFU/100 mL	< 1 CFU/100 mL
Enterococci	**43 %** **250 MPN/100 mL** 15–940 MPN/100 mL	*Not specified*	*Not specified*

Although the overall chi-squared test ($p = 0.0127$) suggested potential variation, small group sizes limit the interpretability of this result. Thus, no robust association between roof material and microbial profile could be established. The detected species point to general environmental contamination rather than clear fecal pollution.

A weak, non-significant correlation between enterococci and coliform counts (Pearson $r = 0.46$, $p = 0.076$) suggests a possible trend, but high variability and limited sample size prevent firm conclusions. Notably, coliform species composition differed significantly between samples with and without enterococci ($Chi^2 = 32.42$, $p = 0.020$), though the practical relevance of these differences appears limited.

In addition to the roof-type comparison, we evaluated MALDI-TOF-MS species profiles across storage types (Fig. 11). A chi-squared test on the full species-by-storage contingency table indicated statistically significant differences ($p < 0.001$). However, we caution against causal interpretation: multiple isolates originated from the same tank (non-independence), colony picking introduces stochasticity in MALDI-TOF profiling, and storage type co-varies with unmeasured factors (e.g., tank age, cleaning frequency, shading, inflow characteristics). Consistent with this, fecal indicator bacteria (***E. coli***, coliforms, enterococci) did not differ significantly across storage types. We therefore report the statistical result but refrain from inferring a storage-type–specific microbial signature.

3.3. Perceptions of people about rainwater

The survey campaigns conducted in CMP also included questions about people's needs and their perception of water usage. In terms of quality of stored rainwater, 55.0 % of the participants think that rainwater quality is at the highest level (Fig. 12). Only 1.8 % and 4.0 % of the participants think that rainwater has a poor quality with scores 1 and 2. Similar results were obtained when people were asked how satisfied they are with using rainwater as an alternative to groundwater. 18.8 % and 31.3 % of respondents have the highest level of satisfaction at levels 4 and 5 in this regard, respectively. Those who do not feel satisfied if they completely used rainwater to replace groundwater (level 1 and 2) accounted for 17.6 % and 14.3 %. Furthermore, Kruskal-Wallis test were applied to evaluate the effect of roof material and water storage on people's perceptions of water quality. The test result ($p = 0.65$ for roof material and $p = 0.45$ for water storage, > 0.05) indicates that no significant differences were detected in Likert- scale ratings of perceived water quality across different roof material and water storage tank. These findings suggest that, within the current sample size, roof material and water storage tank are not a statistically significant factors impacting on the people's perception of rainwater quality.

To delve deeper into people's thoughts about the quality of different water sources, they were asked to choose their favorite type of water. Among available water sources, rainwater is the most popular choice, with 41.0 % of the participants selecting this option, followed by bottled water with 33.7 % (Fig. 13). Although it is considered the best water source in people's opinion, people have their own reasons for not using rainwater for all purposes. 58.7 % of people think they do not have sufficient rainwater, 36.2 % of the participants think that rainwater supply is not reliable all year around, particularly during the dry season (Fig. 14).

Moreover, according to the results of the field trip in 2019, 61.1 % of respondents said that rainwater was the best quality water source (Pham et al., 2023). Two years later, in the context of the world facing to the Covid 19 epidemic, people changed their assessment of the quality of rainwater. After having a more in-depth interview with the people, they shared rumors saying that the Covid 19 virus can spread through the air and enter into rainwater. There were additional rumors that the disposal of human remains during the Covid 19 epidemic could create dust entering the air and rainwater, causing water pollution. From these rumors, a part of people began to form prejudices against the use of

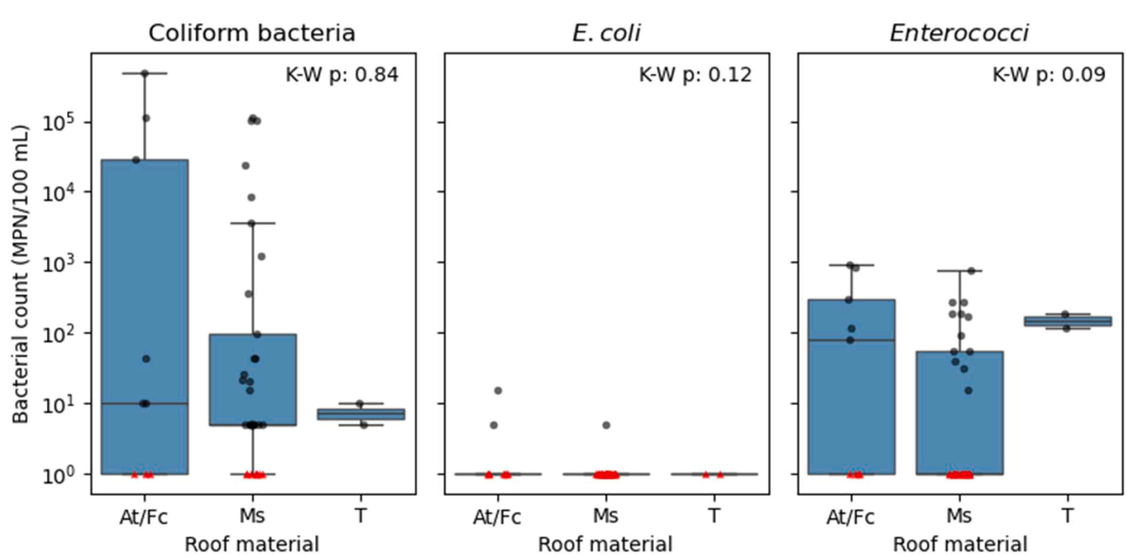

Fig. 8. Concentrations of coliform bacteria, *E. coli*, and enterococci in rainwater storage samples collected from different roof types (At/Fc: asbestos tiles/fibre cement; Ms: metal sheets; T: thatch). Dots represent positive detections; triangles indicate the detection limit for non-detects. Statistical differences between roof types were assessed using the Kruskal–Wallis test; p-values are shown in each plot.

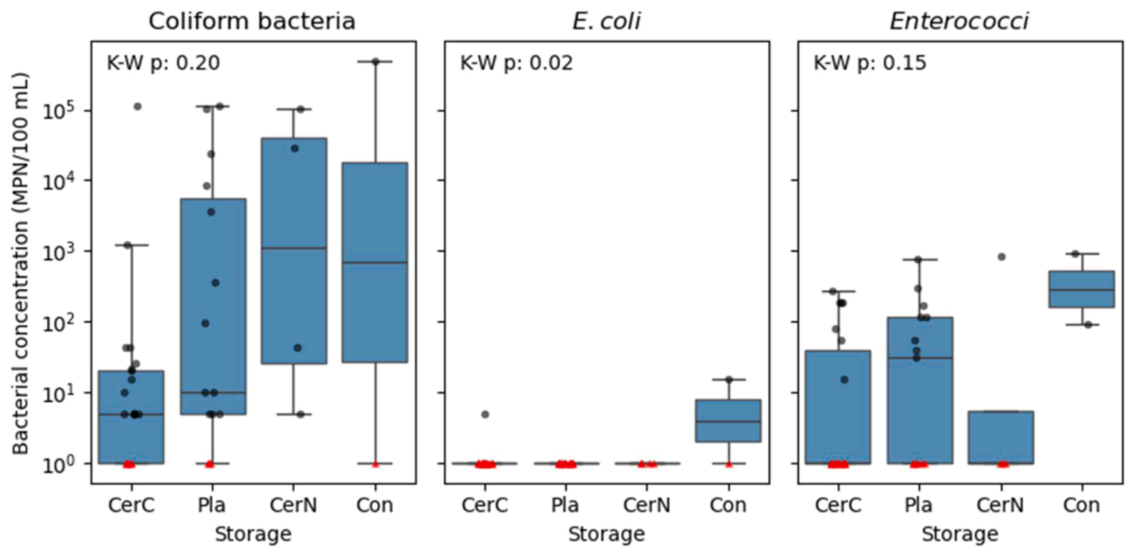

Fig. 9. Concentrations of coliform bacteria, *E. coli*, and enterococci by storage type (CerC: Ceramic with cover, CerN: Ceramic without cover, Pla: Plastic, Con: Concrete); dots indicate positive detections; triangles indicate the detection limit for non-detects. Kruskal–Wallis p-values (Bonferroni-adjusted) are annotated per panel.

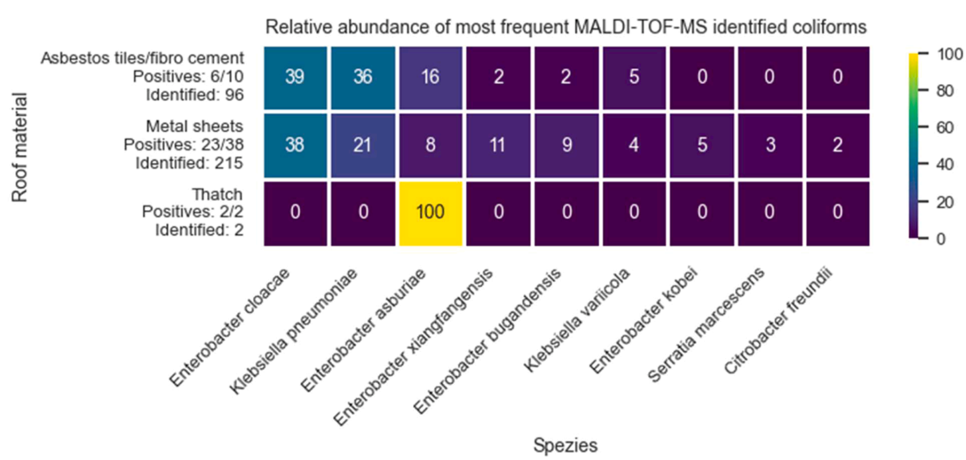

Fig. 10. Relative abundance of coliform bacterial species identified via MALDI-TOF-MS in rainwater samples collected from three roof types. For each group, the number of positive and total samples as well as the total number of identified bacteria is given.

rainwater.

4. Discussion

4.1. Potential of rainwater quantity

Based on time series data from the Integrated Surface Dataset published by the National Oceanic and Atmospheric Administration (NOAA), Fig. 15 shows the changes in the amount of rainwater in both seasons in CMP from the years 1990 to 2021. The dataset highlights the significant difference between the dry season and rainy season. In 2022, total precipitation was 2919 mm, which, taking into account the area of CMP (5274.5 km^2; (General Statistics Office, 2023)), corresponds to a water volume of around 15.4 billion m^3.

The population in CMP in 2022 is 1207,578 people with 275,812 people living in urban area and 931,766 people living in rural area (General Statistics Office, 2022). According to Vietnam Regulation TCXD-VN33:2006/BXD, water demand of people living in rural area is around 40 to 60 liters/person/day, the demand in urban areas considerably higher with around 80 to 150 liters/person/day. The total water demand of residents in the CMP is around 78,306 m^3/day, with 31,718 m^3/d consumed in urban areas and 46,588 m^3/d in rural areas. In one year, the total amount of water that people need for domestic use is therefore around 28.6 million m^3. This calculation indicates, that, if collected and stored efficiently, rainwater could cover people's water demand in CMP.

In addition, Vinh et al. (2024) evaluated potential water availability using a water balance equation under four different scenarios with varying conditions in CMP, including roof catchment area, storage tank capacity requirements, essential domestic water demand during the dry season, and integration with groundwater resources. This study confirmed that the existing roof catchment area is sufficient to meet domestic water demand; however, storage tank capacity must be increased, particularly to ensure water supply during the dry season. Additionally, under the scenario integrating rainwater harvesting with groundwater use, rainwater was able to supply 48 % of domestic water demand, while the extracted groundwater could be effectively recharged by the excess rainwater discharged (Vinh et al., 2024).

4.2. Change in rainwater storage habit for more effective usage

Based on the results from chapter 3.1 and 3.3, it can be concluded

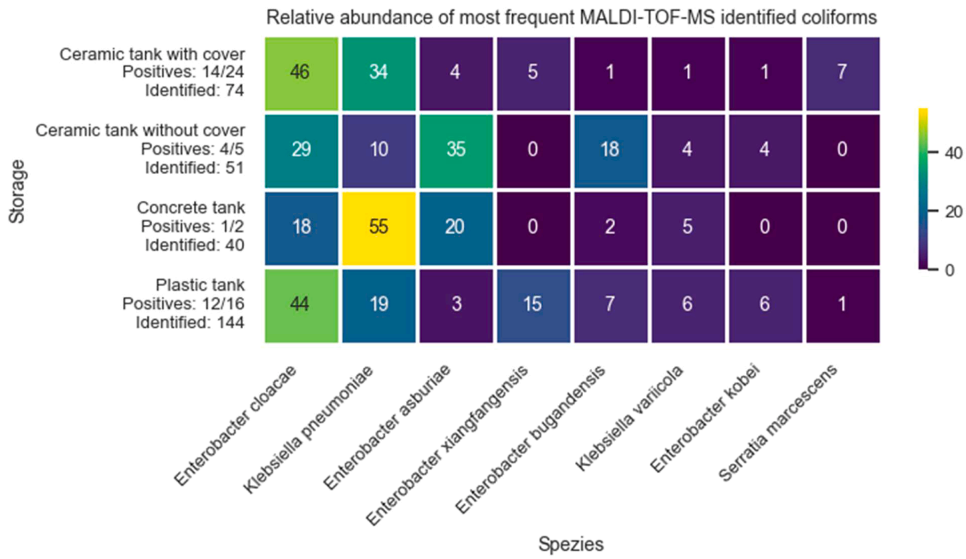

Fig. 11. Relative abundance of coliform bacterial species identified via MALDI-TOF-MS in rainwater samples grouped by storage types. For each group, the number of positive and total samples as well as the total number of identified bacteria is given.

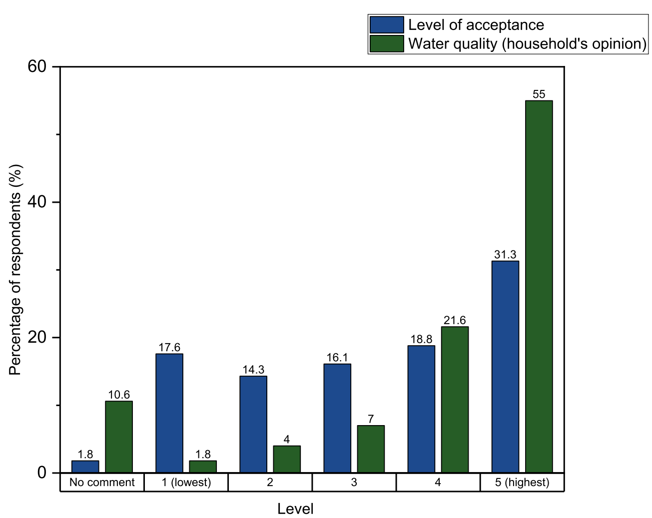

Fig. 12. Household's opinion of rain water quality (green column) and their level of acceptance to use rainwater as a substitute for groundwater (blue column).

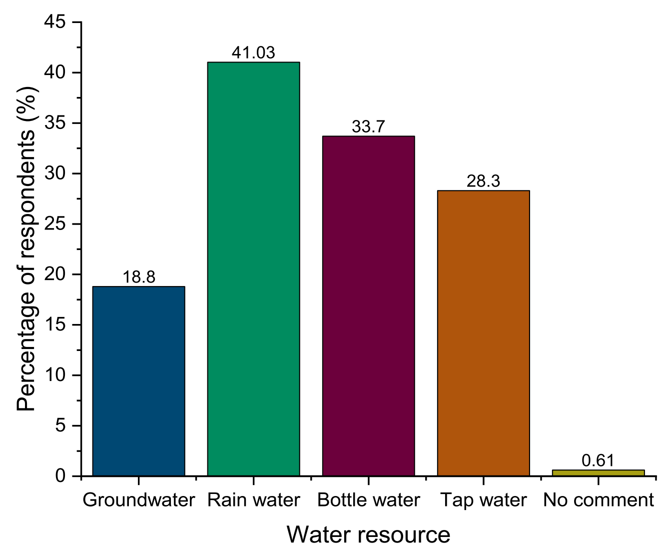

Fig. 13. Best water source in household's opinions.

that CMP residents consider the quality and taste of rainwater to be appropriate, which is why they prefer using it for high-quality purposes such as drinking. In previous studies, direct rainwater quality in the Mekong delta was evaluated as high, with no signs of air pollution and rain quality meets Vietnam National Standard QCVN 02:2009/BYT for most of the parameters (Thu Ha and Hoang, 2014). Most people perceived rain water to be clean, which is why they often use it without further treatment after harvesting. In addition, rainwater quantity stored in vessels and tanks is insufficient for high-consumption purposes such as cleaning and washing. Another study conducted in Tra Vinh province (located in the Mekong Delta) also indicated that rainwater was highly valued for its better taste and its availability during the rainy season. People in Tra Vinh province did not have sufficient containers to collect and store rainwater for use during the dry season (Li et al., 2016). With current storage capacity in Ca Mau, rainwater could not meet the people's demand in the dry season to reduce the groundwater extraction (Vinh et al., 2024).

According to the results of the second survey, rainwater using purposes and rainwater storage equipment changed significantly compared to the result from the first survey in 2019 (Figs. 2,3,4,5). Most obvious is that the number of people using large plastic tanks to store rainwater has clearly increased within two years. Some people use several ways to store rainwater to increase the amount of rainwater. Ceramic tanks were the most commonly utilized and convenient means of rainwater storage in 2019; they were typically covered to maintain water hygiene and to prevent contamination from dust and insects. Plastic tanks with higher quality become currently more popular which also implies that people have invested a certain amount of money in their rainwater storage system. Furthermore, when people have the ability to store more rainwater, their usage purposes also change. Based on the results from Table 1 and the detailed information about water treatment and water use in chapter 3.1, some households use multiple options to treat rainwater before consuming rainwater. The method of treatment depends on the intended use and the economic conditions of households.

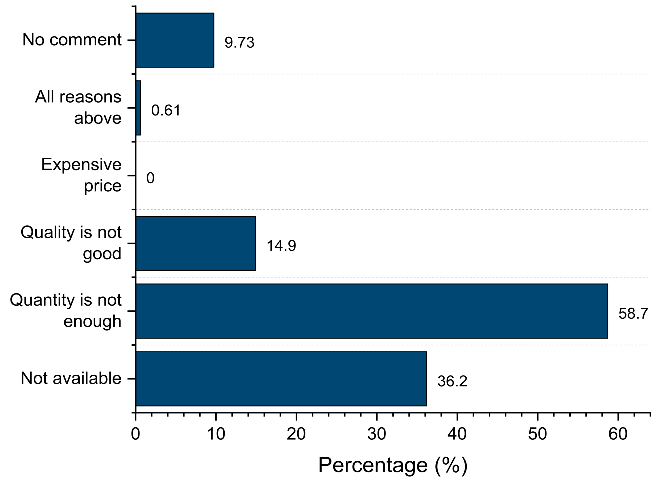

Fig. 14. Reasons why people think rainwater is not suitable for all domestic purposes.

4.3. Potential of rainwater as an alternative to mitigate the impact of groundwater over-extraction

Based on the previous discussion from chapter 4.1, the amount of rainwater can completely serve the water needs of people in Ca Mau, and the Mekong Delta in general. In addition, the study of Vinh et al. (Vinh et al., 2024) also gave similar results on the potential of rainwater in meeting the needs of people based on data from 10 rainwater monitoring stations. According to the assessment of the long term rainfall trend in 2025, the Ca Mau station recorded the highest average annual rainfall in the Mekong Delta of Vietnam (Vuong et al., 2025). However, due to the impacts of climate change, the annual rainfall has shown a decreasing trend. Therefore, it is necessary to implement integrated water resource management and climate adaptation measures to ensure sustainable water use (Vuong et al., 2025).

These results from chapter 3.2 raise the question of why some parameters exceed the limitations. In general, the regular rainwater collection system includes the roofs, pipe systems and storage tanks. When rainwater is harvested, the quality of rain water is affected by roof materials (Olaoye and R.A, 2019). Roof material properties can be one important factor which leads to nonpoint water pollution (Chang et al., 2004). There are three popular roof types including concrete/asbestos tiles, thatch and galvanized metal sheet (Wilbers et al., 2013). In 2019, rain water harvested from asbestos roofing sheet had highest mean value for pH, total hardness, aluminum, cooper, nitrate and sulphate in comparison with another roof types (Olaoye and R.A, 2019). Similarly, rainwater samples in Ca Mau were divided into three different groups based on information from the survey. The difference between the numbers of samples in each group give information on the popularity of different types of roof materials. The difference between the numbers of samples in each group give information on the popularity of different types of roof materials. Water samples with Aluminum concentrations exceeding the standard were in the group from galvanized roofs, contrary to the results of a previous study that rainwater from asbestos roofs had the highest Aluminum and nitrate concentrations (Olaoye and R.A, 2019). After being verified by Kruskal-Wallis statistic, these results indicate that the collected rainwater quality can be influenced by several interacting factors, not only roof types or rain water storage. This supports the assumption that several factors can affect collected rainwater quality, not only roof types, but also pipe system, handling practice, storage duration, people's activities and habits to collect and store water.

Similar findings were reported by Wilbers (Wilbers et al., 2013), who observed that microbial contamination in harvested rainwater was not primarily influenced by roof material but rather by factors such as storage cover type, location, handling practices, and overall hygiene conditions. The presence of coliform bacteria and enterococci in roof-harvested rainwater in chapter 3.2.2 is not unexpected. Fresh rainwater is generally microbiologically clean when it falls, but contamination typically occurs during collection and storage, especially through contact with roof surfaces, bird droppings, gutters, and accumulated debris. Several studies have reported frequent detection of *E. coli*, total coliform and enterococci in rainwater storage tanks, often at concentrations exceeding drinking water standards (Hamilton et al., 2019; Chidamba and Korsten, 2015). Under tropical conditions, such as those in CMP, warm temperatures (25–35 °C), organic matter from roof runoff and stagnant water in storage tanks can create favorable conditions for bacterial persistence and even regrowth (Lleò et al., 2005; Zdeb et al., 2021). While *E. coli* generally declines over time due to its sensitivity to environmental stress, other coliforms such as Klebsiella and Enterobacter identified in this study by MALDI-TOF-MS are more

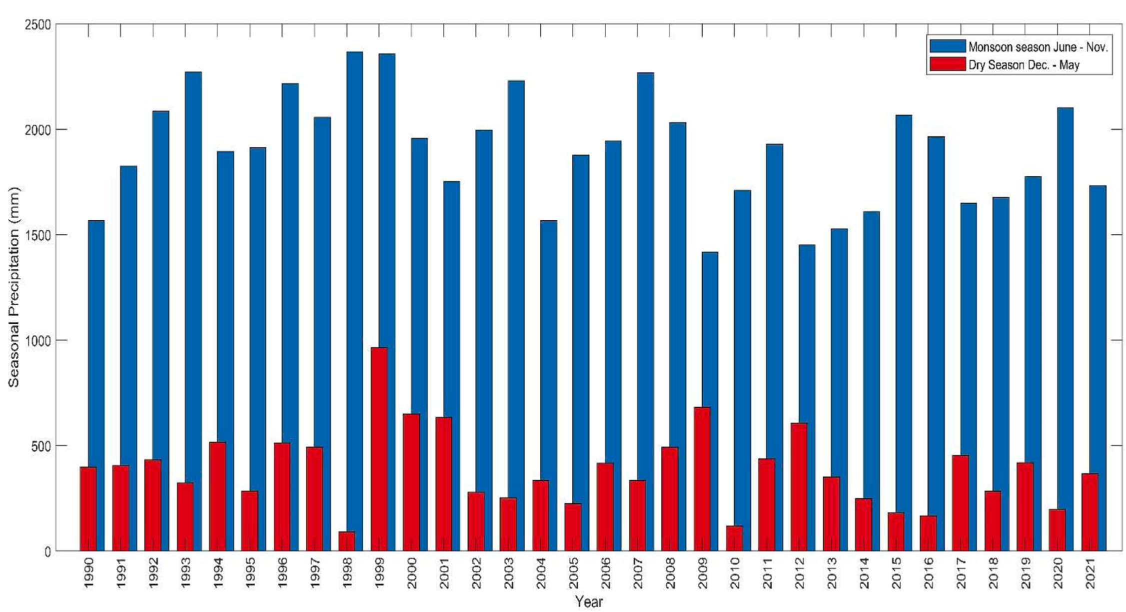

Fig. 15. Changes in rainwater quantity in Ca Mau province during the rainy and dry seasons from 1990 to 2021.

resilient and capable of multiplying in nutrient-rich sediments and biofilms (Martin et al., 2010). Enterococci, although traditionally considered indicators of fecal contamination, are not exclusively of human origin and can also derive from animals or environmental sources (Leister et al., 2023). They are relatively stress-tolerant and can persist for extended periods in stored water. Some studies suggest that under warm, nutrient-enriched conditions, enterococci may survive and even proliferate within biofilms on tank surfaces (Sadanandan and Yogendraiah, 2025; Willett and Dunny, 2024). This highlights the importance of proper tank hygiene and simple treatment measures (e.g., boiling, filtration, or chlorination) before using rainwater for drinking or cooking purposes (Olaoye and Olaniyan, 2019).

In summary, the microbiological analysis indicates that rainwater contamination is primarily due to general environmental exposure rather than specific roof materials or clear fecal sources. No consistent influence of roof type on microbial load was observed. Instead, contamination likely occurs via roof surfaces, and handling practices. Consistent with these findings, the dominance of Enterobacter cloacae in our samples aligns with global assessments of microbial communities in roof-harvested rainwater. Hamilton et al. (Hamilton et al., 2019) reported that environmental coliforms—particularly Enterobacter, Klebsiella, Citrobacter and Serratia—are the most commonly detected genera in rainwater tanks worldwide, whereas *E. coli* typically occurs only sporadically and mainly after recent contamination events. The species profile observed in Ca Mau therefore reflects globally recognized contamination pathways related to dust deposition, plant material, insects and roof biofilms rather than clear fecal pollution. This overlap with global patterns supports the interpretation that microbial contamination in the study area is primarily driven by environmental exposure. According to Vietnamese regulation on drinking water guidelines, the presence of coliform bacteria or enterococci disqualifies rainwater from being considered safe for direct consumption without treatment. To ensure safe use, especially for drinking, basic hygienic standards and appropriate treatment methods such as boiling or filtration are essential. Other studies around the world, which were compiled and reviewed recently, confirmed the high quality of rainwater together with the necessity of treatment before using (Sakati et al., 2023).

In addition, the relationship of groundwater use and rainfall is inversely correlated. For example, a reduction of groundwater extraction was observed during the rainy season in Kenya (Thomson et al., 2019). In Israel, using rainwater for toilet flushing contributed to the reduction of groundwater recharge (Nachson et al., 2022). In addition, groundwater extraction in Ca Mau will become increasingly difficult as shallow aquifers become exhausted or saline (Van Tuan et al., 2024). Water conservation through rainwater harvesting, driven by limited water availability, represents a pathway toward environmental sustainability in many regions of the world (Sakati et al., 2023).

4.4. Attitudes toward rainwater use as alternative water for groundwater and role of government communication in promoting rainwater usage

Following the results from chapter 3.3, the reason behind this perception of water usage is mainly related to concerns about rain water quantity. Some people doubt the feasibility of using rainwater, as the amount of water is inconsistent and not sufficiently available year-round and for all purposes. In another similar study in other provinces of the Vietnam Mekong Delta, rainwater amount is sufficient for households during the rainy season, while during the dry season it is only enough for drinking purpose (Özdemir et al., 2011). Rainwater did not meet the requirements of the local people due to insufficient storage capacity (Vinh et al., 2024). This finding leads to the conclusion that more effective solutions for storing rainwater for domestic use are required. There are several barriers that impede the development of rainwater harvesting in Vietnam, including technical, economic, and social obstacles. Public awareness remains limited due to the spread of unverified information about rainwater quality, lack of knowledge, and insufficient understanding of legal regulations (Nguyen et al., 2019). Peoples lack of system that provides comprehensive information in an easy-to-understand, simple format. In order to prevent misinformation mentioned in chapter 3.3, promoting accurate information to people in a timely manner is very important to raise people's knowledge and awareness. Similar issues arise in many documents dealing with the current state of climate change, but the acute danger posed by land subsidence together with rising sea levels receives less attention (Vo et al., 2025). Vietnam faces water scarcity and saline intrusion, particularly in coastal communities (Bauer et al., 2025; Bauer et al., 2022; Tran and Yong, 2025). Dependence on groundwater among local households increases along the spatial gradient from the northern to the coastal areas. Poor households are particularly vulnerable to domestic water scarcity due to issues such as saline intrusion in groundwater and the lack of alternative water sources (Van Tuan et al., 2024). At the first conference about sustainable development in Mekong Delta, the Vietnamese government emphasized the importance of respecting and adapting to the laws of nature (Linh et al., 2023). To prevent or reduce the over-extraction of groundwater and assure safe water supply also in the future, clear regulation from the government should be formulated and clear benefits of alternative water sources like rainwater should be comprehensively communicated. Our survey together with further discussion with people highlight the factors that affect to people's opinion on changing water resources. Official government announcements are the most important prerequisite for people to comply. It is necessary to implement local-level water management policies, accompanied by proactive actions from local governments, to mitigate environmental impacts and ensure long-term water security in the Mekong Delta (Tran and Yong, 2025). In addition, the high initial investment required for rainwater harvesting systems poses a significant challenge for low-income households (Nguyen et al., 2019). For that reason, residents in CMP expect the encouragement from government to support their change in water sources through financial support to invest e.g. in rainwater storage or tap water distribution.

4.5. Limitations, strengths and future perspectives of the study

This study is based on a limited number of water samples, with relatively few samples corresponding to specific roof materials and storage containers. The number of samples for each material group is uneven due to differences in local prevalence, as some materials have become increasingly scarce in the study area. In addition, microbiological analyses ideally should be conducted directly in the study area; the inability to do so represents a further limitation of this research.

This study adopts a multidisciplinary approach by integrating data from questionnaires, water quality analyses and discussions with local residents to evaluate the potential of rainwater harvesting under specific conditions in CMP. The authors directly collected water samples and engaged with local communities, allowing for a deeper understanding of local perspectives and actual practices. As a result, the methods and findings are highly practical and transferable, and can be applied to similar contexts in other regions. The outcomes of this research contribute to improved water resource management for domestic use and support progress toward Sustainable Development Goal 6.

Future research should expand the study scope by increasing the number of samples and considering additional influencing factors beyond roof materials and storage devices to provide a more comprehensive assessment of rainwater quality. Implementing pilot studies on rainwater harvesting systems would help evaluate their effectiveness in practice. Further investigation into specific case groups using different rainwater storage models tailored to local conditions also represents a promising direction for future work.

5. Conclusion

This study has presented a multi-disciplinary assessment of the potential of collected rainwater as alternative water source for domestic purpose to reduce the groundwater overexploitation in the southern Mekong Delta. Following the results of a previous study (Pham et al., 2023), the present study expanded the number of surveys to improve regional representativeness and the distribution of social and spatial conditions. This study reaffirms the extremely important role of groundwater in people's lives in CMP. In addition, the habit of using alternative water sources such as rainwater was investigated and showed a significant change in the using purpose from mostly using rainwater for drinking purposes in 2019 to other purposes (drinking, cooking and washing) in 2021 and 2022. Along with that, the rain water storage systems also changed; plastic containers became more popular in the most recent years. Respondents typically discard the first flush of rainwater in the beginning of the rainy season to clean the roof and improve the quality of subsequently collected rainwater. The study showed that residents in CMP currently treat rainwater with quite simple methods, mainly settling and filtering through cloth. Based on the evaluation of time-series data, quantity of rainwater in CMP appears sufficient to meet people's demands; nevertheless, appropriate storage infrastructure must be considered. Water quality testing indicates that rainwater is of relatively good quality. However, some physical and chemical parameters, such as pH, nitrate and aluminum, as well as some biological parameters, such as *E. coli* and coliform, exceeded the thresholds in a few samples. In general, the extension of thresholds for certain parameters in the updated version QCVN 01–1:2024 increases the compatibility of rainwater for domestic use. Subsequently, the study examined factors affecting rainwater quality including roof materials and storage tanks. However, it is also necessary to consider additional causes affecting water quality such as the pipe system, the cleaning process of water containers and people's activity. Microbiological analysis showed that contamination was not clearly linked to roof materials or storage conditions but rather to general environmental exposure and human activities. Although various coliform species were detected, the lack of consistent fecal indicators points to non-specific contamination. This observation is particularly relevant given the stricter microbiological standards that will apply from 2024. Therefore, hygienic handling and basic treatment - such as boiling or filtration - remain essential, especially for drinking purposes. According to the individual perceptions of residents in CMP, the quality of rainwater is highly valued and there is a high level of acceptance of using rainwater instead of groundwater. Nonetheless, people would like clearer information from local authorities about the current environmental problems as well as governmental financial support and guidance on water storage practices. This study has opened up a new research direction in selecting suitable pilot locations and designing utilization concept of rainwater to be used as a potential alternative water source to contribute to the reduction of groundwater overexploitation in CMP.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used ChatGPT in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Van Cam Pham: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Johannes Ho:** Writing – review & editing, Visualization, Methodology, Investigation. **Jonas Bauer:** Writing – review & editing, Visualization, Investigation. **Nicolas Börsig:** Writing – review & editing, Project administration, Investigation. **Felix Dörr:** Writing – review & editing. **Tran Viet Hoan:** Writing – review & editing. **Elisabeth Eiche:** Writing – review & editing, Resources. **Andreas Tiehm:** Writing – review & editing. **Stefan Norra:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

Acknowledgment

This research was conducted as part of the ViWaT- Engineering project, funded by the German Federal Ministry of Education and Research (BMBF) under Grant No. 02WCL1474A. We gratefully acknowledge the Vietnamese National Center for Water Resources Planning and Investigation and the Department of Natural Resources and Environment of Ca Mau Province (DONRE Ca Mau) for their kind support. We also thank the laboratory staff of the Institute of Applied Geosciences at Karlsruhe Institute of Technology (KIT), as well as all project partners for their valuable collaboration. Special thanks are extended for the financial support provided through the Graduate Funding from the German States program (Landesgraduiertenförderung) and additional support from the Graduate School for Climate and Environment (GRACE – KIT). Finally, we acknowledge support from the KIT-Publication Fund of the Karlsruhe Institute of Technology.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2026.101443.

Data availability

Data will be made available on request.

References

Ahmed, S.K., 2024. How to choose a sampling technique and determine sample size for research: a simplified guide for researchers. Oral Oncol. Rep. 12, 100662. https://doi.org/10.1016/j.oor.2024.100662. September.

APHA AWWA, W. E. *Standard methods for examination of water and waste water*. 2005.

Bauer, J., Börsig, N., Pham, V.C., Hoan, T.V., Nguyen, H.T., Norra, S., 2022. Geochemistry and evolution of groundwater resources in the context of salinization and freshening in the southernmost Mekong Delta, Vietnam. J. Hydrol. Reg. Stud. 40. https://doi.org/10.1016/j.ejrh.2022.101010.

Bauer, J. et al., "Seawater intrusion in river delta systems. Inter-annual dynamics and drivers of salinity variations in the southern Mekong Delta, Vietnam," vol. 661, no. June, 2025, doi: 10.1016/j.jhydrol.2025.133745.

Bui, D.D., Nguyen, N.C., Bui, N.T., Le, A.T.T., Le, D.T., 2017. Climate change and groundwater resources in Mekong Delta, Vietnam. J. Groundw. Sci. Eng. 4 (2).

Buschmann, J. et al., "Contamination of drinking water resources in the Mekong delta floodplains : arsenic and other trace metals pose serious health risks to population," vol. 34, pp. 756–764, 2008, doi: 10.1016/j.envint.2007.12.025.

Canada, H. *Guidelines for Canadian recreational water quality*. 2024.

Chang, M., McBroom, M.W., Beasley, R.S., 2004. Roofing as a source of nonpoint water pollution. J. Environ. Manag. 73 (4), 307–315. https://doi.org/10.1016/j.jenvman.2004.06.014.

Chau, N.D.G., Sebesvari, Z., Amelung, W., Renaud, F.G., 2015. Pesticide pollution of multiple drinking water sources in the Mekong Delta, Vietnam: evidence from two provinces. Environ. Sci. Pollut. Res. 22 (12), 9042–9058. https://doi.org/10.1007/s11356-014-4034-x.

Chidamba, L., Korsten, L., 2015. A scoping study on the prevalence of *Escherichia coli* and Enterococcus species in harvested rainwater stored in tanks. Water SA 41 (4), 501–508. https://doi.org/10.4314/wsa.v41i4.09.

DONRE Ca Mau, "Ca Mau province water resources master plan to 2025, with orientation toward 2035," 2018.

Dörr, F., Bauer, J., Tran, H.V., Norra, S., Nestmann, F., 2023. Vietnams Mekong-Delta - Landsenkung infolge von Grundwasserübernutzung. Wasserwirtschaft 113 (11), 52–56. https://doi.org/10.1007/s35147-023-1922-3.

Dörr, N., Schenk, A., Hinz, S., 2024. Land subsidence in the Mekong Delta derived from advanced persistent scatterer interferometry with an infrastructural reference network. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 17, 12077–12091. https://doi.org/10.1109/JSTARS.2024.3420130.

Dörr, F., et al., 2025. Passive subsurface characterization in subsiding deltas: assessing land subsidence mitigation potential with frequency analyses of groundwater heads and superposing harmonic drivers. J. Hydrol. 662. https://doi.org/10.1016/j.jhydrol.2025.133844. July.

Danh, V.T. and Khai, H.V. "Household demand and supply for clean groundwater in the Mekong Delta, Vietnam," 2015, doi: 10.1186/s40807-014-0004-7.

Erban, L.E., Gorelick, S.M., Zebker, H.A., 2014. Groundwater extraction, land subsidence, and sea-level rise in the Mekong Delta, Vietnam. Environ. Res. Lett. 9 (8). https://doi.org/10.1088/1748-9326/9/8/084010.

General Statistics Office, "Ca Mau." pp. 69–70, 2022.

General Statistics Office, "Statistical yearbook of Vietnam 2022." pp. 0–1268, 2023.

Hamilton, K., et al., 2019. A global review of the microbiological quality and potential health risks associated with roof-harvested rainwater tanks. NPJ Clean Water 2 (1). https://doi.org/10.1038/s41545-019-0030-5.

Hoan, T.V., Richter, K., Börsig, N., Bauer, J. and Ha, N.T. "An Improved Groundwater Model Framework For Aquifer Structures of the Quaternary-Formed Sediment Body in the Southernmost Parts of the Mekong Delta, Vietnam," 2022, doi: 10.3390/hydrology9040061.

Hoan, T.V., et al., 2025. The utilization of a 3D groundwater flow and transport model for a qualitative investigation of groundwater salinization in the Ca Mau Peninsula (Mekong Delta, Vietnam). Hydrology 12 (5), 1–27. https://doi.org/10.3390/hydrology12050126.

Karlsrud, K., Vangelsten, B.V., Frauenfelder, R., 2017. Subsidence and shoreline retreat in the Ca mau province - vietnam causes, consequences and mitigation options. Geotech. Eng. 48 (1), 26–32.

Leister, C., Reiner, J.E., Grießmeier, V., Gescher, J., Hügler, M., 2023. Gastropods as a source for fecal indicator bacteria in drinking water. Water Res. 244. https://doi.org/10.1016/j.watres.2023.120494. June.

Li, L., Li, C.S., Wichelns, D., 2016. Assessing household willingness to pay for bottled water in rural areas of the Mekong Delta, Vietnam. Water Resour. Rural Dev. 7, 36–49. https://doi.org/10.1016/j.wrr.2016.03.001.

Linh, T., Tran, L., Anh, T., Nguyen, H., 2023. Navigating water policy : vietnam ' s strategic shift in the mekong river basin (2017-2021). Resolusi J. Sos. Polit 6 (1), 60–75. http://doi.org/10.32699/resolusi.v6i1.3704.

Lleò, M.D.M., Bonato, B., Benedetti, D., Canepari, P., 2005. Survival of enterococcal species in aquatic environments. FEMS Microbiol. Ecol. 54 (2), 189–196. https://doi.org/10.1016/j.femsec.2005.03.016.

Martin, A.R., Coombes, P.J., Harrison, T.L., Dunstan, H.R., 2010. Changes in abundance of heterotrophic and coliform bacteria resident in stored water bodies in relation to incoming bacterial loads following rain events. J. Environ. Monit. 12 (1), 255–260. https://doi.org/10.1039/b904042k.

Mekong River Commission, 2019. State of the Basin Report 2018. Mekong River Comm, pp. 1–274 [Online]. Available: http://www.mrcmekong.org/assets/Publications/SOBR-v8_Final-for-web.pdf.

Minderhoud, P.S.J., Coumou, L., Erkens, G., Middelkoop, H., Stouthamer, E., 2019. Mekong delta much lower than previously assumed in sea-level rise impact assessments. Nat. Commun. 10 (1), 1–13. https://doi.org/10.1038/s41467-019-11602-1.

Minderhoud, P.S.J., Middelkoop, H., Erkens, G., Stouthamer, E., 2020. Groundwater extraction may drown mega-delta: projections of extraction-induced subsidence and elevation of the mekong delta for the 21st century. Environ. Res. Commun. 2 (1). https://doi.org/10.1088/2515-7620/ab5e21.

Nachson, U., et al., 2022. New modelling approach to optimize rainwater harvesting system for non-potable uses and groundwater recharge : a case study from Israel. Sustain. Cities Soc. 85, 104097. https://doi.org/10.1016/j.scs.2022.104097. May.

Nguyen, D.C. "Rainwater For Drinking in Vietnam : Barriers and Strategies Bui Thi Thuy, Anh Dung Dao, Mooyong Han Viet Anh Nguyen, Hyunju Park, Pham Dang Manh Hong Luan, Nguyen Thi Thanh Duyen and Hong Quan Nguyen," pp. 585–594, 2019, doi: 10.2166/aqua.2019.054.

Olaoye, O., Olaniyan, R.A, 2019. Quality of rainwater from different roof material. Int. J. Eng. Technol. 2 (8), 1413–1421.

Özdemir, S., Elliott, M., Brown, J., Nam, P.K., Hien, V.T., Sobsey, M.D., 2011. Rainwater harvesting practices and attitudes in the mekong delta of Vietnam. J. Water Sanit. Hyg. Dev. 1 (3), 171–177. https://doi.org/10.2166/washdev.2011.024.

Pechstein, A. et al., "Detailed investigations on the hydrogeological situation in Ca Mau province, Mekong Delta, Vietnam. Technical Report No III-5 of Technical Cooperation Project 'Improving groundwater protection in the Mekong Delta,'" no. December, 2018.

Pham, V.C., et al., 2023. Groundwater use habits and environmental awareness in ca mau province, Vietnam : implications for sustainable water resource management. Environ. Challenges 13, 100742. https://doi.org/10.1016/j.envc.2023.100742. March.

Sadanandan, B. and Yogendraiah, K.M. "Enterococcus faecalis biofilm: a clinical and environmental hazard," p. 5, 2025, doi: 10.3390/msf2025035005.

Sakati, S.N., Mallongi, A., Ibrahim, E., Palutturi, S., Mallongi, A., 2023. Utilization of rainwater as consumable water with rainwater harvesting methods : a literature review. Pharmacognosy 15 (6), 1254–1257. https://doi.org/10.5530/pj.2023.15.227.

Thomson, P., et al., 2019. Science of the total environment rainfall and groundwater use in rural Kenya. Sci. Total Environ. 649, 722–730. https://doi.org/10.1016/j.scitotenv.2018.08.330.

Thu Ha, D., Hoang, H.N., 2014. Proposed solutions for household rainwater collection and storage in the Mekong Delta. Water Resour. Eng. Environ. Vietnam 44, 121–125.

Tran, T.A.N.H., Yong, M.L.I., 2025. Navigating water challenges in the Vietnamese Mekong Delta : how can a shift in water management help? Asia Pac. Issues. 29 (172).

Tran, D.A., et al., 2021. Groundwater quality evaluation and health risk assessment in coastal lowland areas of the Mekong Delta, Vietnam. Groundw. Sustain. Dev. 15, 100679. https://doi.org/10.1016/j.gsd.2021.100679. December 2020.

Van Muoi, L., Srilert, C., Dang, V.P., Van, T.P., 2022. Journal of hydrology : regional studies spatial and temporal variabilities of surface water and sediment pollution at the main tidal-influenced river in Ca mau peninsular, vietnamese mekong delta. J. Hydrol. Reg. Stud. 41, 101082. https://doi.org/10.1016/j.ejrh.2022.101082. April.

Van Tuan, P., Jiang, Y., Stigter, T., Zhou, Y., 2024. Groundwater for sustainable development understanding groundwater use and vulnerability of rural communities in the Mekong Delta : the case of Tra Vinh province, Vietnam. Groundw. Sustain. Dev. 25, 101095. https://doi.org/10.1016/j.gsd.2024.101095. December 2023.

Vanderford, B.J., Mawhinney, D.B., Trenholm, R.A., Zeigler-Holady, J.C., Snyder, S.A., 2011. Assessment of sample preservation techniques for pharmaceuticals, personal care products, and steroids in surface and drinking water. Anal. Bioanal. Chem. 399 (6), 2227–2234. https://doi.org/10.1007/s00216-010-4608-5.

Vinh, D.H., Tran, D.D., Cham, D.D., Thi, P., Hang, T., Man, D.B., 2024. Integrated exploitation of rainwater and groundwater : a strategy for water self-sufficiency in Ca Mau province of the Mekong Delta. Hydrology. https://doi.org/10.3390/hydrology11040055.

Vo, T.M.H., et al., 2025. How consistent are adaptation strategies with ongoing climatic and environmental changes in the Vietnamese Mekong Delta: a systematic review. Environ. Sci. Policy 168. https://doi.org/10.1016/j.envsci.2025.104064. January.

Vuong, H., et al., 2025. Assessment of long - term rainfall trends and variability in the vietnamese mekong delta : implications for water resources management strategies. Discov. Environ. https://doi.org/10.1007/s44274-025-00233-7.

Wartalska, K., et al., 2024. The potential of rainwater harvesting systems in europe – current state of art and future perspectives. Water Resour. Manag. 38 (12), 4657–4683. https://doi.org/10.1007/s11269-024-03882-0.

WHO, 2022. Guidelines For Drinking-Water quality: Fourth edition Incorporating the First and Second Addenda. World Health Organization, pp. 1–614.

Wilbers, G.J., Sebesvari, Z., Rechenburg, A., Renaud, F.G., 2013. Effects of local and spatial conditions on the quality of harvested rainwater in the Mekong Delta, Vietnam. Environ. Pollut. 182, 225–232. https://doi.org/10.1016/j.envpol.2013.07.019.

Willett, J.L.E., Dunny, G.M., 2024. Insights into ecology pathogenesis, and biofilm formatio of Enterococcus faecalis from functional genomics. Microbiol. Mol. Biol. Rev. 89. https://doi.org/10.1128/mmbr.00081-2323.

Yamane, T. *Introductory analysis*. 1973. doi: 10.2307/2311831.

Zdeb, M., Zamorska, J., Papciak, D., Skwarczyńska-Wojsa, A., 2021. Investigation of microbiological quality changes of roof-harvested rainwater stored in the tanks. Resources 10 (10). https://doi.org/10.3390/resources10100103.

Zoccarato, C., Minderhoud, P.S.J., Teatini, P., 2018. The role of sedimentation and natural compaction in a prograding delta : insights from the mega mekong delta, Vietnam. Sci. Rep. 1–13. https://doi.org/10.1038/s41598-018-29734-7. January.